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DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

INSTRUMENTATION FOR A SUBCRITICAL HOMOGENEOUS SUSPENSION REACTOR

Under the direction of Prof. J. J. Went, in the laboratories of N.V. Keuring van Electrotechnische Materialen ("KEMA"), Arnhem, an unusual type of nuclear reactor is being developed, viz. a homogeneous suspension reactor. Comprehensive measurements have been made on a small subcritical model (which has operated close to the critical state). The results led to the decision to construct a second experimental model, on which various chemical processes can be studied and which can generate a power of several hundred kW.

The development work, commissioned by the Netherlands Reactor Centre, is being carried out by a team composed mainly of research staff from the KEMA and the Reactor Centre. The instrumentation for the reactor is the fruit of close cooperation between this team and Philips, and was built partly by KEMA and partly in the Philips Research Laboratories, Eindhoven.

In the first article of the series printed below, Dr. Went explains the background to this research project. The second article deals with the measurement of non-nuclear-physical operating parameters on the subcritical reactor. The other articles are concerned with the instruments designed for neutron-flux measurements and for safety purposes.

I. REASONS BEHIND THE CHOICE OF A HOMOGENEOUS SUSPENSION REACTOR

by J. J. WENT *).

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The conversion of nuclear energy into energy of a useful form takes place in a nuclear reactor. The importance of this new type of energy source, in view of the world's dwindling reserves of conventional fuels, needs no emphasis here. Although various high-power reactors are in course of construction at the present time, it is by no means established which of the different fundamental possibilities is to be preferred (not to mention the purely constructional details). Investigation of these fundamental matters is still in full progress. Among the countries so occupied, The Netherlands is adding her contribution. The *credo* behind the unconventional type of reactor being developed by the KEMA — the homogeneous suspension reactor — and the reasons why initially a subcritical model was built (i.e. one that delivers no energy), will be set forth in this article.

The basic principles of nuclear reactors are to be found in the many books and articles on the sub-

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ject [1]), and will not be discussed here. Very generally the following are some of the significant points that need special attention in the development of a nuclear reactor.

Reactor physics:

1) the conditions under which the reactor becomes critical (i.e. under which a fission chain reaction is sustained);
2) the kinetic behaviour of the reactor;
3) the degree to which fresh fissile material can be "bred" during operation.

Engineering, chemical and materials problems:

1) the efficiency and the simplicity of the means of extracting heat from the reactor;
2) the form in which the fissile material is present in the reactor (in a "fuel element" or in a circulating liquid);
3) keeping the radioactive fission products safely together;
4) the simplicity with which the fission products can be removed from the reactor;
5) corrosion problems in the reactor.

Review of reactor systems

To explain the choice of a homogeneous suspension type of reactor, it will be helpful to review and classify the various reactor systems. Although any classification is bound to be subjective, the following will be useful for our purpose.

"Fast" reactors and "thermal" reactors

The first question to be decided is whether the reactor is to be a "fast" or a "thermal" type, that is whether the nuclear fissions are to be effected by "fast" or by "thermal" (slow) neutrons. Neutrons are said to be *fast* when their kinetic energy is about 2 MeV and therefore equal to the energy acquired by neutrons released in the fission process. When fast neutrons are slowed-down in a moderator until their speed ("temperature") corresponds to the temperature of the moderator — i.e. about 0.025 eV at 300 °K — they are called *thermal* neutrons. As regards the probability of undergoing fission by capturing a fast or a thermal neutron, the isotopes of uranium, plutonium (Pu) and thorium behave very differently. This probability is expressed in the *effective fission cross-section* σ_f, the unit for which is the *barn* ($= 10^{-24}$ cm^2). In *Table I* the values of σ_f are given for some U, Pu and Th isotopes in the case of fast and thermal neutrons. The large cross-section which ^{235}U, ^{239}Pu and ^{233}U possess for thermal neutrons implies that a thermal reactor is much easier to bring into the critical state than a fast reactor. On the other hand a fast reactor has the advantage that, when a fissile nucleus captures a fast neutron, the average number of fresh neutrons released is greater. This average number, η, is also given in Table I. A large η favours the breeding of new fissile material, as will presently be explained.

Table I. Effective fission cross-section σ_f of various fissile nuclei for thermal and for fast neutrons, and the average number η of neutrons released per captured neutron.

Nucleus	Thermal neutrons of 0.025 eV (300 °K)		Fast neutrons of 2 MeV	
	σ_f barns	η	σ_f barns	η
^{235}U	580	2.08	1.3	2.3
^{238}U	0	—	0.5	2.55
^{239}Pu	750	2.06	2.0	2.8
^{232}Th	0	—	0.1	—
^{233}U	530	2.28	2.1	2.4

Thermal reactors of the heterogeneous and homogeneous types, with solid or liquid fuel

Thermal reactors can be subdivided into two groups in two ways. The first takes account of the manner in which the fissile and moderator materials are distributed, i.e. either heterogeneously (separated from each other), or homogeneously mixed. The reactors are accordingly referred to as heterogeneous or homogeneous thermal reactors, as the case may be. Another classification is concerned with the state of aggregation of the fissile material, i.e. whether it is in solid or liquid form. Although these two classifications need not run parallel, the following two combinations are nevertheless the ones that first come to mind:

1) the heterogeneous thermal reactor with solid fuel in the form of fuel elements, surrounded by the moderator, or
2) the homogeneous thermal reactor with liquid fuel, i.e. with the fissile material dissolved or suspended in e.g. water (H_2O or D_2O), which acts as the moderator.

A third combination, however, is also practicable, and was in fact under investigation, namely a heterogeneous system using a liquid fuel; for example a graphite-moderated system through which a solution of ^{233}U in molten bismuth is circulated (known as the "liquid-metal fuel reactor").

[1]) See e.g. D. J. Littler and J. F. Raffle, An introduction to reactor physics, Pergamon Press, London 1957; S. Glasstone, Source book on atomic energy, Macmillan, London 1958. For a very abbreviated introduction, see Philips tech. Rev. **19**, 246-248 and 256-257, 1957/58.

The "breeding" of fresh fissile material; conversion factor

Before going into the pros and cons of the groups into which we have just classified nuclear reactors, we shall briefly discuss the fissile materials used. This will clarify the classification of reactors into fast and thermal types, and in particular will explain why our work has been concentrated on the homogeneous thermal reactor using liquid fuel.

The fissile isotopes that occur naturally are ^{238}U and ^{235}U (found in natural uranium in the percentages 99.3 and 0.7%, respectively) and ^{232}Th, the latter in a quantity comparable to that of natural uranium. Of these only ^{235}U is fissionable both by thermal and fast neutrons (see Table I). ^{238}U and ^{232}Th can be split only by fast neutrons, and even then the probability of this happening is extremely small. This does not mean, however, that ^{238}U and ^{232}Th are of no use in a thermal reactor. Neutrons can be captured by nuclei of ^{238}U and ^{232}Th, giving rise to unstable isotopes. These decay via a series of disintegrations, involving β^- emissions, into fresh fissile isotopes, ^{239}Pu and ^{233}U, respectively:

$$^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U \xrightarrow[23.5\ \text{min}]{\beta^-} {}^{239}_{93}Np \xrightarrow[2.33\ \text{days}]{\beta^-} {}^{239}_{94}Pu,$$

$$^{232}_{90}Th + {}^{1}_{0}n \rightarrow {}^{233}_{90}Th \xrightarrow[23.5\ \text{min}]{\beta^-} {}^{233}_{91}Pa \xrightarrow[27.4\ \text{days}]{\beta^-} {}^{233}_{92}U$$

(n = neutron, Np = neptunium, Pa = protactinium; the times mentioned are the half-lives for the β disintegration). Thus, fresh fissile material is "bred" in the reactor, which is accordingly called a "breeder". These breeding reactions are important in the first place in that a greater fraction of the invested fissile material undergoes fission. Another important point is that the fresh fissile materials can be bred in sufficient quantities to start other nuclear reactors after the needs of the production reactor have been met.

The efficiency of the breeding process is expressed by the *conversion ratio C*, which is the ratio of the average number of fissile nuclei of ^{239}Pu or ^{233}U formed per second from ^{238}U or ^{232}Th, to the average number of fissile nuclei ^{235}U, ^{239}Pu or ^{233}U destroyed per second. For example, $C = 0.80$ means that the reactor, by breeding, meets 80% of its own fuel requirements, so that in principle, apart from the readily available quantity of "fertile" material, i.e. ^{238}U or ^{232}Th, the reactor needs to be supplied with only 20% of the amount of fissile material that would otherwise be necessary. $C = 1$ means that the breeding process completely meets the reactor's fuel requirements, and $C > 1$ means that the reactor produces an excess of fissile material.

Since fissile materials are much dearer than fertile or source material, the general tendency will be to economize on fissile material as far as possible by adopting the breeding principle, that is to build reactors having a high conversion ratio. There are economic limits to this, however. In the case of a reactor for a power station, for example, there is no object in cutting down on fuel costs unless, per kWh produced, they represent a considerable percentage of the total cost of a kWh. The limit will approximately be reached at $C = 0.95$ (where the invested fissile material constitutes only $^1/_{20}$th of the amount consumed). There is accordingly little point in trying to achieve a higher value of C, unless it is possible to make the reactor produce so much excess fissile material as to make it worth while employing this excess in other reactors.

The value of C obtainable is closely related to the magnitude of η (see table I). Of the average number of neutrons, η, released when a fissile nucleus captures a neutron, one serves in the first place for being captured in its turn by another fissile nucleus, thus sustaining the chain reaction. Of the remainder, $\eta - 1$, part is lost through various causes, such as "leakage" at the surface of the reactor proper and absorption in the moderator, in the structural materials and possibly in the fission products, and part is available for the conversion of ^{238}U into ^{239}Pu or of ^{232}Th into ^{233}U. Suppose that $C = 1$; then for compensating the leakage and absorption losses per fission there remain only $\eta - 2$ neutrons available, and these will be sufficient only if η is materially larger than 2. Referring to the values of η given in Table I, we find the following.

1) For fast neutrons η is always greater than for slow.
2) For fast neutrons ^{239}Pu has by far the largest η, namely 2.8.
3) For thermal neutrons ^{233}U has by far the largest η, namely 2.28.
4) For thermal neutrons ^{239}Pu has a small η (i.e. 2.06) and — which is not to be seen from the table — this value drops rapidly as the neutron energy increases. At an energy corresponding to 600 °K, for example, η has already dropped considerably below 2.

The above figures lead to several important conclusions, which are summarized below.

a) A *fast* reactor fuelled by ^{239}Pu, bred from ^{238}U, can have a conversion ratio substantially higher than 1. Because of the small σ_f of ^{239}Pu for fast

neutrons, however, the density of ^{239}Pu atoms in the reactor will have to be very great to achieve criticality (*fig. 1*). Highly enriched plutonium must therefore be used. The fertile material (in this case ^{238}U) surrounds the Pu as a blanket, in which leaking neutrons are usefully employed. From time to time the generated Pu must be chemically separated from the blanket and suitably processed before being supplied to the reactor as fuel.

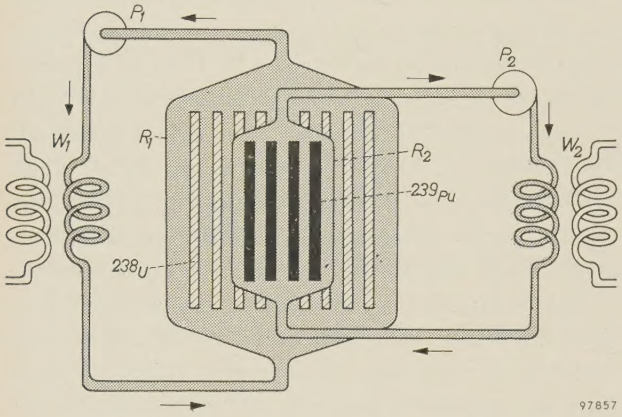

Fig. 1. Schematic cross-section of a fast reactor fuelled by ^{239}Pu bred in the reactor from ^{238}U. R_1 outer reactor vessel containing elements of fertile material (solid ^{238}U). R_2 inner reactor vessel (core) with fuel elements containing solid ^{239}Pu. Liquid sodium is circulated as coolant through both vessels. P_1, P_2 circulation pumps. W_1, W_2 heat exchangers, delivering steam.

b) A *thermal* reactor fuelled by ^{233}U, bred from ^{232}Th, can have a conversion ratio of $C = 1$ provided the neutron conservation is adequate. Owing to the large effective cross-section of ^{233}U for fission by thermal neutrons ($\sigma_f = 530$, see Table I), it is possible to make this kind of reactor critical even with quite low concentrations of ^{233}U. Thus the fertile material can also be accommodated inside the reactor system, so that the fuel material bred from it is immediately available for fission. This dispenses with the need for chemical separation and the supply of fresh fissile material, which is unavoidable under (*a*).

c) Although we have specially emphasized under (*a*) and (*b*) the importance of the fissile materials ^{239}Pu and ^{233}U, which can be bred in fast and thermal reactors, it should be remembered that ^{235}U is likely to remain the basic fuel of nuclear reactors for some time to come. This is after all the only directly fissile material that occurs naturally, and for this reason constitutes at present the basic material for any nuclear energy programme.

Classification of reactors according to conversion ratio

Since the conversion ratio C is one of the quantities determining the choice of a given type of nuclear reactor, it will also be useful to classify reactors according to the magnitude of C.

1) Reactors operating exclusively with highly enriched fissile materials. This type will be preferred where small, mobile reactors are required and where the price of the fissile material is not a primary consideration. Such reactors employ scarcely any fertile material, and therefore C will be zero or very small.
2) Normal thermal reactors, fuelled by ^{235}U or by ^{239}Pu bred from ^{238}U, in which a conversion ratio between 0.6 and 0.85 is often obtainable. Such a value is clearly favourable for fuel economy.
3) Thermal reactors breeding ^{233}U from ^{232}Th and with the utmost in neutron economy, having a value of C from 0.9 to 1.1. In these reactors the fraction of the original charge of fissile material that undergoes fission is high enough to make the use of thorium practicable. Provided the chemical processing involved is not excessively costly, the fuel costs can in fact be very low.
4) Fast reactors that breed ^{239}Pu from ^{238}U (fig. 1), with C values from 1.5 up to 1.8. Such reactors are capable of producing so much ^{239}Pu as to enable the excess to be employed for fuelling other reactors, fast or thermal. The practical value of this is somewhat limited, however, by the fact that up till now it seems difficult to use Pu in thermal reactors, for one reason because of the unfavourable value of η (see above).

Choice of reactor type

An important quantity in a nuclear reactor is the *multiplication factor* k of the neutrons, which is the ratio of the number of neutrons in a given "generation" to the number in the preceding generation, the lifetime of a generation being about 10^{-3} sec in thermal reactors and about 10^{-7} sec in fast reactors. The value $k = 1$ is required if the chain reaction is to be just self-sustaining. If $k < 1$, the number of neutrons present decreases with time. If $k > 1$, the number increases and the reactor is said to have a positive *reactivity*. The latter quantity is defined as $(k - 1)/k$.

When changes in reactivity occur, no matter what the cause, the kinetic behaviour of the reactor becomes of importance; for certain fundamental reasons this behaviour can give rise to greater difficulties with fast than with thermal reactors. Reactor kinetics are closely bound up with safety. In a densely populated country like The Nether-

lands, safety is a particularly serious consideration, and our attention was therefore turned primarily to thermal reactors. On the other hand, greater economy in the use of reactor fuel is certainly not devoid of interest, especially in The Netherlands which is poor in fissile material. The obvious course, then, was to consider a thermal type of reactor, capable of breeding ^{233}U as fuel from ^{232}Th whilst making the most economical use of neutrons. For starting this reactor, ^{235}U or ^{239}Pu might be used.

The moderator would have to be chosen for optimum neutron economy. The best in this respect is heavy water. Furthermore, as little use as possible should be made of neutron-absorbent structural materials inside the reactor. The absorption of neutrons in the fission products and the leakage of neutrons from the reactor should be minimized.

All these requirements point towards a homogeneous reactor with the fissile material distributed in heavy water. In the core of this type of reactor there is no need for any structural materials. For the purpose of heat extraction the homogeneous reactor medium circulates through an external heat-exchanger. The direct transfer of energy from the fluid medium can be highly efficient, being proportional to the temperature difference (which is limited, of course) between the inlet and outlet, and to the pumping speed, which is subject to merely practical restrictions. A power extraction of 40 MW per cubic metre reactor volume seems well within the bounds of possibility.

Advantages can further be derived from the circulatory system by passing the reactor medium through a decontamination plant to remove the strongly neutron-absorbent fission products, such as ^{135}Xe and ^{149}Sm, so rapidly that only few neutrons are lost to these substances. In heterogeneous reactors the fission products are retained in the fuel elements and the neutron losses are consequently higher.

Comparison of homogeneous and heterogeneous reactors

Technologically, a homogeneous reactor of the type described has little in common with the more conventional heterogeneous types. The main difference is that it does not contain the costly fuel elements, with their limited lifetime, that have to be installed in heterogeneous reactors. On the other hand, these fuel elements have the merit of retaining the radioactive fission products, which in a homogeneous reactor are freely circulated. Since part of the circulatory system is outside the reactor proper, namely the heat exchanger and the circulation pump, the system must be completely leak-tight, to prevent the dangerous dispersion of radioactive substances; the demands in this respect are even higher than those made on the protective shield around the fuel elements in a heterogeneous reactor, which are entirely enclosed in the core.

Another notable difference concerns the control and safety systems. To keep the neutron flux constant — and hence the generated power — *heterogeneous* reactors are equipped with a control mechanism consisting of one or more rods of a neutron-absorbent material, such as boron. The neutron flux is controlled by varying the depth to which these rods are inserted in the core. A safety mechanism is required for automatically shutting-down a heterogeneous reactor if the neutron flux should become excessively high. This may be done by causing the control rods, or similar "safety rods", to drop into the reactor [2]), or by "poisoning" the reactor with a boron injection. An important advantage of the *homogeneous* type of reactor described is that it does not require control and safety rods. There are two reasons for this. The nuclear energy is released primarily as kinetic energy from the nuclear fragments formed upon fission, and this energy in a homogeneous reactor is directly transferred to the water. Now the first favourable circumstance here is the high thermal expansion coefficient of water; the expansion reduces the moderating action of the water so as to give the reactivity a high negative temperature coefficient. This is also the case, of course, in water-moderated reactors of the heterogeneous type. Secondly — and this applies solely to homogeneous reactors — the temperature coefficient works promptly, owing to the virtually immediate transfer of energy from the fission fragments to the water. The consequence is that the production of neutrons is automatically retarded by the rising temperature.

In most of their other technical features, too, homogeneous and heterogeneous reactors are completely disparate. *Table II* gives a schematic comparison of both types in terms of complexity. Without allocating a specific weighting factor to each of the points mentioned, and thereby evaluating some numerical measure of the degree of simplicity, it cannot be said which type is to be preferred. A proper assessment must necessarily be based on experience of the construction and operation of both types, which should preferably be at least as large as a power demonstration reactor. Heterogeneous reactors of this size are already fairly

[2]) See e.g. M. van Tol, Monitoring, control and safety equipment for a nuclear reactor of the swimming-pool type, I. General description, and F. E. L. ten Haaf, G. Klein and F. J. Schijff, II. Further description of certain component units, Philips tech. Rev. **19**, 245-257 and 273-285, 1957/58.

Table II. Comparison of some major problems of homogeneous and heterogeneous thermal reactors, in terms of complexity.

Nature of problem	Homogeneous reactor with circulating fuel	Heterogeneous reactor with stationary fuel
Core construction	Simple	Complex
Heat extraction	Complex (leak-tight circulatory system)	Simple
Control of reactivity	Simple (negative temperature coefficient)	Complex (control and safety rods)
Control of fission-product dispersion	Complex (fission products inside and outside reactor)	Simple (fission products retained in fuel elements)
Fuel element	Simple (solution or suspension)	Complex (canned elements)
Plant maintenance	Complex (entire circulatory system is radioactive)	Simple (intense radioactivity confined to core)
Chemical processing and reprocessing	Simple	Complex
Heat extraction per m^3 volume	Very high	Moderate to high
Corrosion	Difficult problem	Difficult problem

numerous, but only very few homogeneous reactors have so far been built. It is therefore not yet possible to pronounce definite judgement on which type is more desirable for a particular application. The construction of the homogeneous subcritical reactor to be described below, in which the fuel is kept in circulation, represents an attempt to fill some of the gaps in our knowledge of homogeneous reactors.

Further details of the homogeneous reactor with circulating fuel

The concept "homogeneous reactor with circulating fuel" is still not fully defined even if we add the information that the reactor breeds ^{233}U from ^{232}Th and is moderated by heavy water to achieve maximum neutron economy. The two principal questions still to be decided are:

1) whether the reactor is to consist of two zones, i.e. of a core surrounded by a fertile (breeder) blanket, or of one zone only;
2) whether use is to be made of a solution or a suspension (slurry).

These two questions are to some extent related. Let us take question (1) first.

A reactor having a fertile blanket can in principle have a higher conversion ratio than a one-zone reactor. This is not only because the blanket turns the leaking neutrons to a useful purpose again, but also has to do with the properties of the intermediate product ^{233}Pa which is obtained in the formation of ^{233}U from ^{232}Th:

$$\underset{\sigma_c = 7.5}{^{232}_{90}\mathrm{Th}} + {}^{1}_{0}\mathrm{n} \rightarrow \underset{1400}{^{233}_{90}\mathrm{Th}} \xrightarrow[23.5\ \mathrm{min}]{\beta^-} \underset{70}{^{233}_{91}\mathrm{Pa}} \xrightarrow[27.4\ \mathrm{days}]{\beta^-} \underset{55\ \mathrm{barns}}{^{233}_{92}\mathrm{U}}\ .$$

The neutron-capture cross-section, σ_c, of ^{233}Pa is 70 barns as against 7.5 barns for ^{232}Th, and the disintegration of ^{233}Pa into ^{233}U has a half-life of almost a month. During this relatively long half-life there is thus an appreciable probability that the ^{233}Pa nuclei will capture neutrons, producing ^{234}Pa, which does *not* transform into the fissile ^{233}U (fissile because its $\sigma_f = 530$ barns $\gg \sigma_c$). The probability of the unwanted formation of ^{234}Pa depends not only on the σ_c of ^{233}Pa and its half-life but also on the neutron flux at the point considered, to which the probability is proportional. If steps are taken to ensure that the ^{233}Pa (and hence also the fertile material ^{232}Th) only occurs where the neutron flux is low, i.e. on the outside of the reactor, the loss of ^{233}Pa, and of neutrons for the chain reaction, resulting from the formation of ^{234}Pa, will be small. This consideration would therefore lead to the arrangement of the fertile ^{232}Th in the form of a blanket around a core of the fissile ^{233}U, i.e. to a reactor composed of two zones (*fig. 2a*).

The reactor in course of development in The Netherlands is *not* being built on this principle. This is mainly because there are two serious drawbacks attaching to reactors with two zones: their construction is more complicated than that of one-zone reactors (compare fig. 2*a* with fig. 2*b*), and to find a suitable material for the core vessel is a most difficult problem (see below). The advantage set against these drawbacks, i.e. the higher conversion ratio, is not of great significance in our case, since it would result in only a relatively slight reduction of the cost of a kWh (the cost of the fissile material being a relatively small percentage of the total).

The structural complexity of two-zone reactors

arises from the necessity of providing them with two distinct cooling circuits and with two different chemical processing systems (see fig. 2*a*). The latter are needed for the following reasons.

a) Chemically pure ^{233}U must be separated from the blanket and then supplied, in the appropriate form, to the reactor core in order to replenish the spent fuel. At the same time the blanket must be rid of the products of corrosion, erosion and fission (erosion is caused by the solid suspended particles when a suspension is used). Apart from being an unwanted complication, the chemical processing which this involves adversely affects the conversion ratio, since it is inevitably accompanied by some loss of ^{233}U and thus the "effective" conversion ratio will be somewhat lower than the "physical" conversion ratio.

b) The reactor core must be rid of fission products such as ^{135}Xe, which would be harmful to the conversion, and also of corrosion and erosion products.

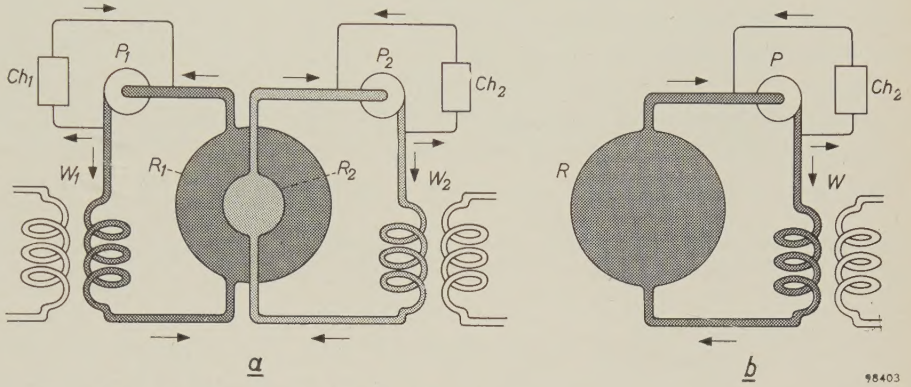

Fig. 2. Schematic representation of two homogeneous reactors.
a) Two-zone homogeneous reactor: outer vessel R_1 with a circulating suspension of ThO_2 (breeding blanket), inner vessel R_2 with a circulating solution of UO_2SO_4 in water. P_1, P_2 circulation pumps. W_1, W_2 heat exchangers. Ch_1 chemical plant which 1) separates ^{233}U and ^{232}Th and processes the ^{233}U, and 2) removes products of corrosion, erosion and fission. Ch_2 chemical plant for removing fission, corrosion and erosion products.
b) One-zone reactor, with vessel R, circulation pump P and heat exchanger W through which circulates a suspension of ThO_2-UO_2 particles (fertile and fissile material) in water. Ch_2 chemical plant as in (*a*). A great advantage of the one-zone reactor is that it does not require the chemical plant Ch_1 as in (*a*), nor does it involve the difficulty of finding a suitable material for the wall of R_2.

On the other hand, in a one-zone reactor (fig. 2*b*) the generated ^{233}U can participate directly in the fission process, without any intermediate stage. The chemical separation plant referred to under (*a*) is therefore not required, which represents a considerable simplification.

The dividing wall between the core and the blanket in a two-zone reactor must obviously be highly permeable to neutrons. It must also be resistant to corrosion from various sources, namely from the liquids with which it is in contact, high temperatures, β and γ radiation, high neutron flux and bombardment by fission products. As yet the best compromise between permeability to neutrons and resistance to corrosion is a zirconium alloy known as zircaloy. It is doubtful, however, whether this material would prove sufficiently resistant to corrosion under the conditions mentioned.

It is a simpler matter to find a good material for the wall of a one-zone reactor, the requirement of permeability to neutrons not being applicable here. The wall can be protected against fast neutrons and high-energy fission products by interposing a "thermal shield" of a material that slows neutrons down to low velocities.

We now come to the question as to the form in which the fissile material should be circulated: as a solution or as a suspension. Let us first consider the two-zone reactor. In its *core* this type requires fissile material only, and that in a very low concentration (about 0.05% by volume), fertile material being undesirable there in view of the ^{234}Pa that would then be formed. If we choose the fissile material in the form of oxide particles suspended in water, it is difficult, owing to the high specific gravity of these particles (approx. 10 g/cm^3), to maintain with such a low concentration a sufficiently homogeneous distribution throughout the primary circulatory system. With a solution in water of, say, uranyl sulphate (UO_2SO_4) it would be easier to maintain the necessary homogeneity, provided at least the temperature and the radiation caused no precipitation of the solution. In the *blanket*, on the other hand, the concentration of fertile material must be high (5 to 10% by volume), in order to absorb all the neutrons leaking from the core. The relevant Th or U salts, however, are not sufficiently soluble, and moreover concentrated sulphate solutions would be excessively corrosive. This means that only a suspension (of oxide particles) can be used in the blanket of a two-zone reactor.

The above also applies to a one-zone reactor in which the fissile and fertile materials are mixed (approx. concentration 3% by volume).

The question, "solution or suspension?", can thus be answered as follows: a two-zone reactor can probably operate on a solution and a suspension; a one-zone reactor that also produces fresh fissile material must operate on a suspension.

For special purposes one can also have a one-zone reactor that does not produce fresh fissile material, i.e. one that only generates heat, without conversion necessarily taking place. This type, called a "burner" reactor, can operate on pure ^{235}U or ^{239}Pu. By virtue of the arguments given above for the core of a two-zone reactor, a very dilute solution can be used in this case.

To give the reader an idea of the possible dimensions and of the invested quantities of nuclear and moderator (D_2O) materials, we have set out in *Table III* some general data concerning a burner

Table III. Broad comparison of three types of homogeneous reactor with circulating fuel. Heat production 440 MW at 300 °C max.

Feature \ Reactor type	Burner reactor with ^{235}U or ^{239}Pu	Breeder reactors with ^{232}Th		
	1 zone	2 zones		1 zone
		core	blanket	
Fissile material	$^{235}UO_2SO_4$ solution	UO_2SO_4		ThO_2-UO_2
Fertile material	—		ThO_2	
Concentration (grams/litre)	2	6	500-1000	300
Concentration of fissile material (%)	100	100	very low	1.5
Diameter of vessel (metres)	3	1.5	3	3.6
Conversion ratio C	0	approx. 1.1		approx. 1.0
Quantity of D_2O (metric tons)	30	30		45
Quantity of fissile material (kg)	65	90		200
Quantity of fertile material (metric tons)	0	11		14

reactor, a two-zone breeder reactor and a one-zone breeder reactor. The figures assume a maximum heat production of 440 MW at a maximum temperature of 300 °C, giving an electric power output of about 100 MW. The amounts of nuclear and moderator material take into account the required cooling circuit outside the reactor vessel. The table reveals an advantage of the two-zone reactor not hitherto mentioned, namely that this type calls for a substantially smaller investment in nuclear material and heavy water than the one-zone type. At present this advantage does not offset the drawbacks mentioned above, no more than does the higher conversion ratio.

The design and development of the homogeneous one-zone suspension reactor

Having been led by the above considerations to decide in favour of a homogeneous one-zone suspension-type reactor, we were faced by problems that may be divided into three groups:

1) Problems concerning the stability of the reactor (also during start-up and shut-down).
2) Problems relating to the chemical processes in the reactor and the separation of impurities in the ancillary circuits, including the removal of corrosion products.
3) General engineering and structural problems.

With a view to solving the problems under (1) a small subcritical reactor was built. This will henceforth be called reactor I, and will frequently be referred to in the subsequent articles in this series. The results of the tests on reactor I were encouraging and a second, smaller reactor is now under construction (reactor II), designed for a power output of about 250 kW. This will be used for studying the processes mentioned under (2). The third step, it is hoped, will be the construction of a prototype of a high-power one-zone suspension reactor.

Reactor I operates on the principle illustrated in fig. 2*b*. The system is shown again in *fig. 3*, with some important details added. By means of the valve T_1 a variable amount of the circulated suspension can be diverted through the shunt pipe *Sh*,

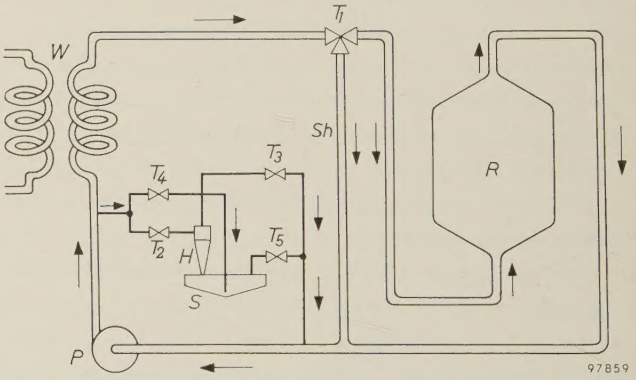

Fig. 3. Simplified diagram of the subcritical suspension reactor (reactor I) built by KEMA. *R* reactor vessel. *P* circulation pump. *W* two-stage heat exchanger (cooler) which transfers its heat via a closed water circuit to the main cooling water. *Sh* shunt pipe across reactor vessel. T_1 control valve. *H* hydrocyclone which, when valves T_2 and T_3 are open, separates fuel particles from the suspension. *S* reservoir in which the separated fuel is collected. To add fissile material to the reactor circuit it is necessary to open valves T_4 and T_5.

thus regulating the flow through the reactor vessel *R* (the circulation pump *P* operates at a constant speed). Fig. 3 also shows how the concentration of fissile material in the suspension is controlled. To withdraw fissile material from the suspension,

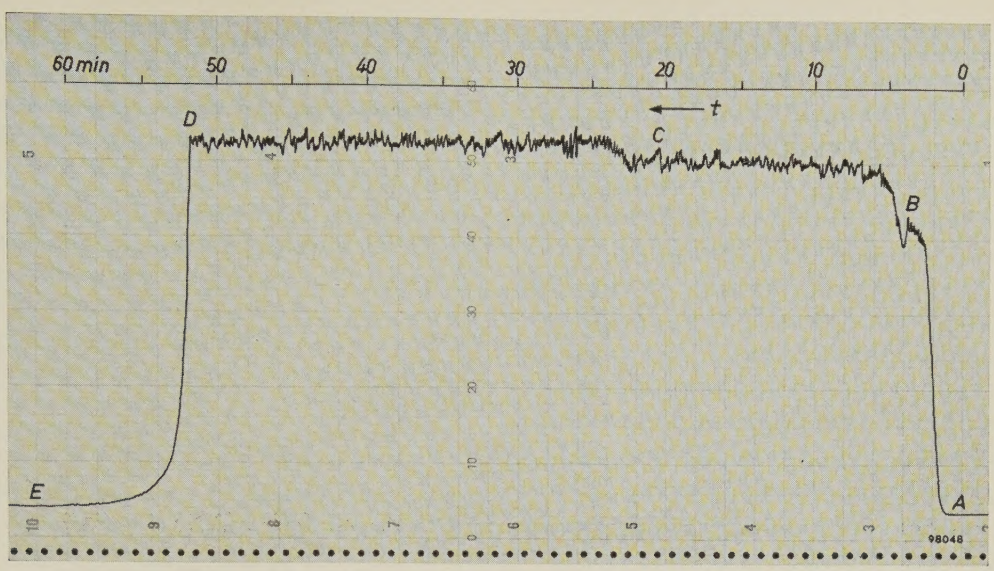

Fig. 4. Recording of the neutron flux Φ in the KEMA subcritical reactor, as a function of time t. To the right of A the neutron flux had the initial value Φ_0, delivered by an external neutron source; at this point the reactor contained water only.

A marks the point at which UO_2 particles were introduced into the reactor circuit from the reservoir; Φ rapidly increased as a result of the fission of ^{235}U nuclei. At B the connection with the reservoir was momentarily interrupted, at C closed. At D the hydrocyclone came into operation, removing fuel particles from the suspension. After some minutes, at E, the reactor vessel was again depleted of fuel, returning the neutron flux to the starting value Φ_0. The fluctuations in the curve are due to statistical fluctuations in Φ.

valves T_2 and T_3 are opened. Part of the suspension then flows via T_2 to a hydrocyclone H in which the solid particles are centrifugally separated from the water. These fuel particles are collected in a reservoir S, whilst the water returns via T_3 into the main circuit. To draw fresh fuel into circulation from the reservoir, valves T_4 and T_5 are opened; a jet of water then enters the reservoir and forces fuel particles into the main circuit. In this way the fuel concentration can be very accurately controlled.

Fig. 4 shows a recording of the neutron flux Φ in reactor I. D marks the point where the valves T_2 and T_3 (fig. 3) were opened, setting the hydrocyclone into operation and causing Φ to drop rapidly to the initial value Φ_0, supplied by an external source of neutrons (see below).

We shall now deal at greater length with the stability problem, mentioned above, after which we shall discuss briefly the chemical, materials and engineering questions.

Physical stability

We have seen that, owing to the high negative temperature coefficient of its reactivity and the promptness with which this becomes effective, a water-moderated homogeneous reactor is inherently stable. The reactivity is regulated by corresponding changes in the temperature of the reactor. Consequently, no control and safety mechanism is required, a fundamental physical mechanism — the thermal expansion of water — being responsible for control and safety in this type of reactor. There is thus no possibility of a dangerous thermal "run-away", as there is in a heterogeneous reactor if the control system is defective.

What has, however, to be taken into account is the danger that a sudden transition to a higher equilibrium temperature resulting from a sudden increase in the concentration of the fissile material might cause a wave of high pressure that could damage the reactor vessel. It is therefore necessary to determine the maximum magnitude and speed of temperature variations that can arise in such a reactor, both under normal and abnormal conditions. An abnormal condition would occur if, e.g., the reactor circulation were to be suddenly stopped without the fuel particles first having been withdrawn from the reactor. Even greater difficulties would result if, after such an abrupt shut-down, the reactor were to be suddenly started again. In that case the distribution of the particles in the main circuit would be initially very heterogeneous and would only gradually become homogeneous. The consequence would be temporarily severe changes in reactivity, hence in neutron flux. Investigations in this connection should consist of measuring the neutron-flux variations in a reactor which is either slightly subcritical, or critical at so low a power level as to keep the radioactivity of the reactor core as low as possible and

prevent large temperature excursions. In the first place this will mean that, owing to the extremely low power production, so little heat will be generated that the above-mentioned stabilizing action of temperature fluctuations will not be effective; the neutron-flux variations will thus be relatively greater and can therefore be more accurately measured. In the second place the low level of radioactivity will enable modifications to be made to the installation more readily.

Not only is it desirable, for the reasons mentioned, to limit the temperature excursions; as one of the principal operating parameters, the temperature must in fact be kept accurately constant. This is done by an electronic regulating device to be described in article II of this series.

In these tests, then, temperature variations with their stabilizing effect are deliberately excluded, and so some other safety mechanism must be adopted, e.g. normal control and safety rods containing boron. Three such rods are accordingly fitted in reactor I; they are mounted in the neutron reflector which surrounds the reactor core (*fig. 5*) and which will be touched on presently. The insertion of these rods can reduce the reactivity by up to 6%.

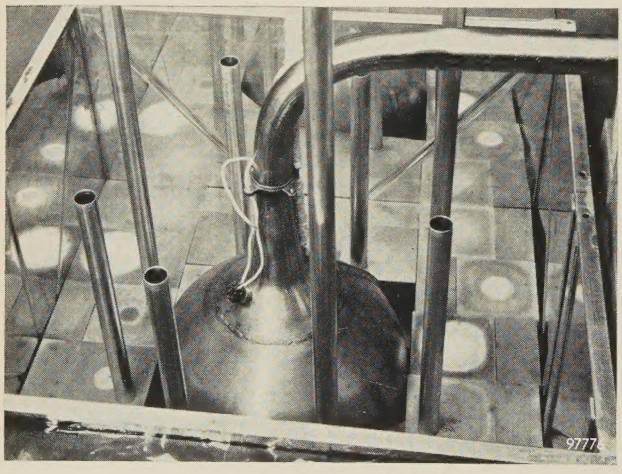

Fig. 5. The reactor vessel in the KEMA reactor I. Of the eight vertical tubes three serve as guides for the control and safety rods; the five shorter tubes each contain a neutron detector. The blocks (partly removed) inside the four walls are of beryllium oxide; together with blocks of graphite outside the walls, they constitute a neutron reflector. The reactor vessel is of stainless steel; it has a capacity of 18 litres and measures 30 cm in diameter. A temperature sensing element is fitted to it.

The neutron flux must not, of course, be made arbitrarily small, particularly because it is also required to measure transient fluctuations in the neutron flux: in a given short time a sufficient number of neutrons must have been counted to prevent statistical fluctuations in the neutron flux from influencing the measurement. We therefore stipulated that, in general, it should be possible to detect 40 000 neutrons per second.

We have referred above to measurements in a reactor in the subcritical state. This is a state in which the multiplication factor k is less than 1. The neutron flux can then be maintained only provided neutrons are continuously supplied to the system.

This can be done with the aid of a radium-beryllium source, in which the alpha rays emitted by radium react with the beryllium as follows:

$$^4_2\mathrm{He} + ^9_4\mathrm{Be} \rightarrow ^{12}_6\mathrm{C} + ^1_0\mathrm{n}.$$

Another kind of neutron source makes use of an accelerating tube, producing the reaction

$$^2_1\mathrm{D} + ^2_1\mathrm{D} \rightarrow ^3_2\mathrm{He} + ^1_0\mathrm{n}.$$

Reactor I is provided with both types of neutron source.

Suppose that the external neutron source constantly supplies N neutrons per second. After n neutron generations the total neutron production, i.e. the production of source and reactor together, will be (for $n \gg 1$):

$$Nk\,(1 + k + k^2 + \ldots + k^n) \approx N\frac{k}{1-k}$$

neutrons per second.

(Since the lifetime of one generation is approximately 10^{-3} second, this state is reached in, say, 0.1 sec.) The neutron flux caused by this production can now be measured. If k varies by an amount δk, then, where N is constant, the quantity $Nk/(1-k)$ will also vary, the more so the more k approaches unity [3]). If we measure k and also the neutron-flux variations, we can calculate δk. Of course, the temperature must be kept carefully constant during these measurements. If the temperature slowly rises — e.g. as a result of the pump energy dissipated in the water — the required quantity δk will have a variation $\delta' k$ superimposed on it, depending on the temperature increment and the negative temperature coefficient of the reactivity. For our purposes the temperature was required to remain constant within ± 0.1 °C.

Finally, a word about the determination of the conditions for criticality (the geometry of the reactor, the temperature T of the core and the concentration c of the fissile material in the water),

[3]) The effect of *delayed* neutrons is left out of account here. This is not permissible, however, if k closely approaches unity, since the delayed neutrons (about 0.7% of the total number released) apparently have a much longer lifetime (approx. 10 seconds) than the "prompt" neutrons (approx. 10^{-3} sec).

i.e. the conditions under which k becomes exactly equal to unity. Since $Nk/(1-k)$ is then infinitely large, it is a relatively simple matter to determine the required conditions. If we plot $(1-k)/N$ as a function of c, with T constant, we obtain a curve as shown in *fig. 6*. From subcritical plots we can thus find the critical concentration c_{cr} by extrapolation. The magnitude of δk for small changes in concentration is then fairly easy to derive from c_{cr}.

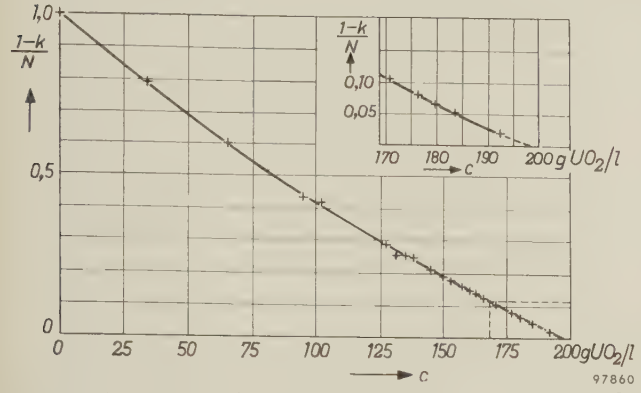

Fig. 6. The quantity $(1-k)/N$ plotted on an arbitrary scale as a function of fuel concentration c, the temperature T of the reactor medium being kept constant. The crosses represent measurements on the KEMA reactor I for a given arrangement of neutron source and neutron detector, and at $T = 25$ °C. The concentration c_{cr} at which, under these conditions, the reactor would become critical is found by extrapolation (see inset); in this case $c_{cr} = 198$ grams UO_2 (uranium with 20% ^{235}U) per litre suspension.

The following articles in this series will describe the instrumentation for the above measurements in reactor I, jointly developed by the Arnhem team and Philips Research Laboratories at Eindhoven. The electronic equipment can be seen in *fig. 7*. The following are some of the conditions which the installation was designed to meet:

a) Reactor I was to be fitted with control and safety rods.

b) The core temperature was to be kept automatically constant within $\pm$ 0.1 °C in the range from 20 to 80 °C.

c) The external neutron source had to be sufficiently intensive to allow the neutron detectors to count as many as 40 000 neutrons per second in the absence of fissile material. On the other hand it was necessary to be able to make the source so weak as not to cause $Nk/(1-k)$ to become too high, despite the high value of $k/(1-k)$.

d) The operation of the neutron detectors with their associated electronic equipment was to remain linear even at values far in excess of 40 000 neutrons per second.

e) It was necessary to be able to measure and vary continuously the concentration of the suspension.

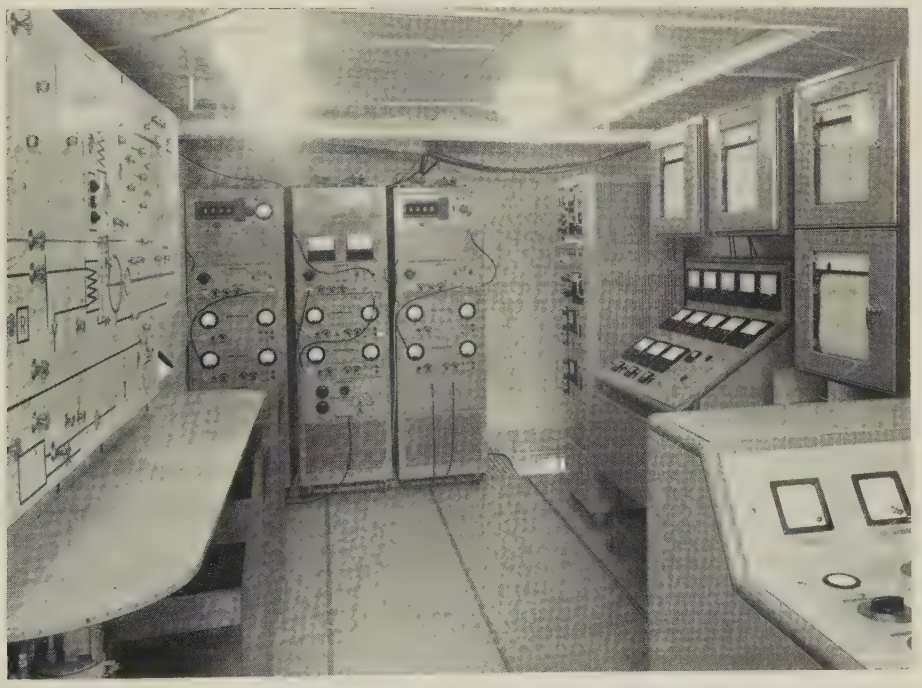

Fig. 7. Electronic part of the instrumentation for the KEMA reactor I. Left: graphic panel of installation. Centre, background: neutron counters. Right, moving towards foreground: temperature regulator, neutron-flux meters and equipment for control and safety rods; meters for recording temperature and concentration of the suspension in the reactor vessel, the rate of flow (in m^3/h), and the coolant temperature; control desk for the accelerating tube of one of the neutron sources.

Chemical processes in the reactor

Many chemical processes taking place in a suspension reactor can be studied just as well in a small as in a large reactor, provided there is not much difference in their temperature and radiation conditions, or in their suspension properties (such as concentration per unit volume and the properties of the particles). The operating temperature is set by adjusting the concentration of the suspension. Equivalent radiation conditions can be obtained by ensuring that the small reactor produces the same power per unit volume as the large one, i.e. just as many fissions per second and per cm^3. The power is adjusted by regulating the extraction of heat from the heat exchanger (fig. 2*b*). Furthermore it is desirable that the volumetric concentrations of fissile and fertile material in the small reactor should be just as high as in the large. This condition can be met if the ratio between the numbers of fissile and fertile atoms is independently adjustable.

Thus, under the conditions prevailing in a large power reactor, a small "process reactor" can be used for studying, *inter alia*: the effect of radiation on the decomposition of water, the colloid-chemical stability of the suspension and the mechanical stability of the suspended particles under the influence of the fissions that occur in them, the extraction of the fission products in processing circuits and the removal of corrosion and erosion products.

With a view to studying these processes, a second small reactor of this type (reactor II) is under construction at the KEMA laboratories. It is as small as is practicable from the viewpoint of reactivity. That there is a lower limit to the volume of the reactor vessel follows from the fact that, as the vessel is reduced in size, the surface area decreases less rapidly than the volume; neutron leakage thus becomes relatively greater and would finally become unworkably large. The lower limit of the dimensions can be reduced by compensating more or less for the increasing leakage of neutrons. To this end, the vessel in reactor I is surrounded by a neutron *reflector* of a good moderating material, consisting of a layer of beryllium oxide surrounded by graphite (fig. 5). This, in conjunction with the use of enriched fuel (20% ^{235}U), made it possible to suffice with a volume of 18 litres. With these very small dimensions less fuel is required to make the reactor critical when it is moderated with ordinary instead of heavy water. Reactor I is therefore fuelled by a suspension of uranium oxide (UO_2) in ordinary water, and so also will be reactor II, since for studying the processes in question it makes virtually no difference which kind of water is used.

The conversion ratio of reactor II cannot be high, nor is it intended to be, for the object with this reactor is to investigate quantitatively the processes that should be optimized in order to achieve a high conversion ratio in a power reactor.

General materials and engineering problems

No less important are the materials and engineering problems. In this article, however, they need only be touched on very briefly.

In the type of reactor with which we are concerned the circulating fluid is exceptionally radioactive, and moreover the material of the entire main circuit is made radioactive by delayed neutrons (otherwise left out of account here). As a result, two groups of problems are encountered that are far less serious in a reactor in which the fuel is not circulated.

First of all, steps must be taken to ensure that all components of the reactor system — pumps, valves, etc. — are absolutely and permanently leak-tight. Secondly, there is the question of maintenance. A life of 20 years is estimated for a normal electric power station. No power plant is conceivable with such a life in the absence of provisions for periodic maintenance. A nuclear reactor must therefore be designed to allow for proper maintenance — obviously with facilities for remote control.

The process reactor (II) in course of construction will provide important data on both problems. The information will not, however, be complete. Further progress must necessarily relay on experience with components on the scale of a power reactor, and on experience of the maintenance costs involved. The third step in our development programme will therefore be to build a prototype of a power reactor. It need hardly be said that this will be a very costly step indeed.

Summary. At the KEMA laboratories at Arnhem work is in progress, under the auspices of the Netherlands Reactor Centre and under the direction of the author, on the development of an unconventional type of nuclear reactor — a one-zone homogeneous suspension reactor. After distinguishing between fast and thermal reactors, and classifying the latter into heterogeneous and homogeneous types, the author discusses the "breeding" of fresh fissile materials (^{239}Pu and ^{233}U) from "fertile" materials (^{238}U and ^{232}Th, respectively). The efficiency of the breeding process is expressed in the conversion ratio, the magnitude of which is taken as a further basis for classifying reactors.

In a densely populated country like The Netherlands, with its shortage of fissile material, considerations of safety and nuclear fuel economy indicate the use of a homogeneous reactor with circulating fuel. This leaves a choice between a two-zone reactor (i.e. one with a core of fissile material surrounded by a blanket of fertile material) and a one-zone

type (in which fissile and fertile materials are mixed). The latter type was preferred, mainly because it is less complicated. The circulated fluid consists of a suspension of ThO_2 particles containing some UO_2 in heavy water, the latter also acting as moderator. The fissile material is ^{233}U, bred in the reactor itself from ^{232}Th.

The first step in the development programme was to build a small-scale reactor of this type for experiments in the subcritical state. The neutron flux is maintained by an external neutron source. The circulated fluid is a suspension of UO_2 (natural uranium with 20% ^{235}U) in ordinary water. One of the quantities determined was the fuel concentration required to achieve criticality. As a second step a similar reactor (process reactor) is being built, designed for a power output of 250 kW and on which various chemical processes will be studied under conditions comparable to those in a large power reactor. The third step will be to build a prototype power reactor of the homogeneous suspension type.

II. MEASUREMENT AND CONTROL OF OPERATING PARAMETERS

by B. L. A. van der SCHEE *) and M. van TOL.

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In the experiments with the subcritical suspension reactor in one of the laboratories of N.V. KEMA at Arnhem [1]), the temperature in the reactor vessel must be kept rigorously constant (variations $<$ 0.1 °C) at any required value between room temperature and 100 °C. It is also necessary to be able to measure certain operating parameters, chief among which are, apart from the reactor-vessel temperature, the concentration of the suspension in the reactor vessel and the rate at which the suspension is pumped around the reactor circuit. In this article we shall discuss in turn the control devices for keeping the *temperature* constant [2]), the instruments for measuring the *concentration* and those for measuring the *rate of flow*. Finally we shall review the whole reactor system together with its instrumentation (but not the equipment for neutron-flux monitoring and for operating the control rods, which will be dealt with in subsequent articles).

Temperature control

The design of the temperature control system had to take account not only of the permissible maximum deviation of the temperature, but also of the fact that 3 to 7 kW of energy is supplied to the fluid by the pump that keeps the suspension circulating in the reactor circuit. This means that even at the highest operating temperature (below the boiling point) some cooling is necessary. The operating temperature is determined by the degree of cooling. The stabilizing of the temperature against variations in the power dissipated by the pump, etc., is effected by applying somewhat excessive cooling, and by compensating the excess with the aid of a variable heater element, which surrenders its heat directly to the suspension. The heater element is controlled by a thermometer, which measures the temperature of the suspension. This method of stabilization is in the present case more rapid and sensitive than one in which the coolant flow is varied. In the state of equilibrium the heater gives up about half its maximum power (5 kW), making it possible to offset variations of more than 2 kW in the power to be dissipated.

The system is represented schematically in *fig. 1*. Cooling takes place in two stages. Between the

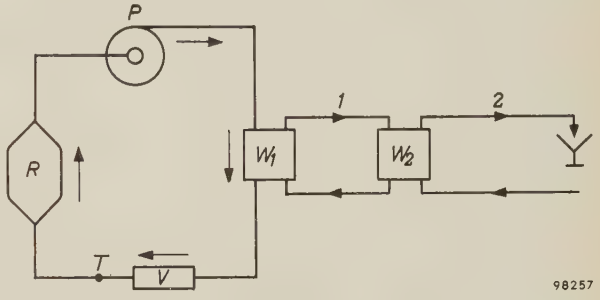

Fig. 1. Schematic representation of reactor circuit with the primary (*1*) and secondary (*2*) cooling circuits. *P* pump. *R* reactor vessel. *V* heater. W_1 primary cooler. W_2 secondary cooler. *T* thermometer in control system.

coolant pipeline *2* (through which main water flows that passes out into the drains, i.e. ultimately into the Rhine) and the reactor circuit, there is a closed-circuit coolant system, which excludes the possibility of radioactive substances being discharged into the river. The closed circuit is called the *primary* cooling system, the other the *secondary* cooling system.

It will also be noted that the thermometer element for the control system is not situated inside the reactor vessel — whose temperature is the decisive quantity — but in the line between the heater and the vessel. The choice of this position was prompted

*) Formerly with the R.C.N.-KEMA team, Arnhem, The Netherlands.

[1]) See article I of this series, J. J. Went, Instrumentation for a subcritical homogeneous suspension reactor, I. Reasons behind the choice of a homogeneous suspension reactor, Philips tech. Rev. **21**, 109-121, 1959/60 (No. 4/5). Designed and supplied by Philips.

by the following considerations. Owing to the relatively large volume of the reactor vessel there is a fairly long time-interval between the moment at which the heater delivers too much (or too little) heat, and the moment at which a thermometer situated in the reactor vessel responds to the change. The rate of flow in the vessel is low and one cannot always be sure that the contents are thoroughly mixed. Of course, this time interval can be shortened by stirring, thus limiting it virtually to the time taken by the fluid to pass through the pipe between heater and vessel (the distance-velocity lag). A further small improvement is gained by using a highly sensitive thermometer (or by increasing the loop gain). Even then, however, the interval will still be fairly long. The combination of a long distance-velocity lag and a high loop gain can easily make the circuit unstable. Placing the thermometer immediately after the heater shortens the lag sufficiently to make it easy to keep the control system stable.

The fact that it is not the temperature in the reactor vessel that is kept constant, but the temperature at the output of the heater, is no objection in the operating conditions involved here. In the first place the suspension does not remain long enough in the reactor vessel to cool down appreciably — the fluid is circulated twice to four times per minute — and secondly in a subcritical experiment virtually no energy is generated in the reactor vessel by the nuclear fissions.

In one respect it is even an advantage to place the thermometer before the reactor vessel. Since, owing to mixing, a degree of temperature equalization takes place in the vessel, and the heat capacity of the whole contents is relatively high, rapid periodic variations in the temperature of the influent do not significantly affect the temperature in the vessel. This means that the control circuit (now consisting of a short section of pipeline, a thermometer and an apparatus via which the thermometer controls the heater) need not be critically damped; a possible damped oscillation of the control system has practically no effect on the temperature in the vessel. If the reactor vessel were an integral part of the control circuit, critical damping would be essential.

It may be concluded from the foregoing that the control system is required to do no more than compensate for the variations in the power dissipated in the fluid by the pump and the variations in the power withdrawn by the cooler (which are a consequence of variations in the temperature of the water in the secondary cooling circuit). These variations are always slow and cause a temperature change in the reactor circuit of no more than a few tenths of a degree per hour. Thus, the disturbances to be eliminated are these slow temperature fluctuations of the water entering the heater. The heater power need not be varied more than from 0 to 5 kW for this purpose. Only if the temperature of the cooling water goes on rising or falling during a whole working day may the variability of the heater power be found to be inadequate. In that case it will finally be necessary to alter the setting of the coolant valve. This does not significantly detract from the effectiveness of the control system. There is ample time for such an intervention and moreover it is seldom necessary.

In principle a much lower power would suffice (e.g. 2 kW). A maximum heater power of 5 kW was chosen, however, because the heater is used not only for control purposes but also for heating the suspension prior to the experiment. Moreover, the relatively wide limits within which the heater power is variable make the setting of the cooling capacity less critical.

The temperature changes corresponding to the power contributions of pump, cooler and heater are obviously related to the volume of suspension flowing past any point per unit time. In normal conditions this is 7.5 m^3 per hour. The pump then supplies a power of about 5 kW, the heater an average of 2.5 kW (max. 5 kW), giving 7.5 kW in all. The temperature difference between the inlet and outlet of the cooler is about 1 °C, and between the input and output of the heater 0.7 °C at the most.

Control system

The suspension is heated by simply passing an electric current through part of the stainless-steel pipeline which, together with the reactor vessel, forms the reactor circuit. This method has the virtue of requiring no leads through the pipe wall. The section of pipe serving as heater element measures about 1 metre in length and has an inside diameter of 32 mm. Its electrical resistance is 1.4×10^{-3} Ω, so that for a heat production of 5 kW the current through the pipe wall must be 1900 A. This current is obtained by means of a specially designed transformer (primary voltage 220 V, secondary voltage 3.5 V, secondary current 2500 A max.). The secondary winding is joined to the ends of the heater element via flexible copper strips brazed to copper blocks (*fig. 2*).

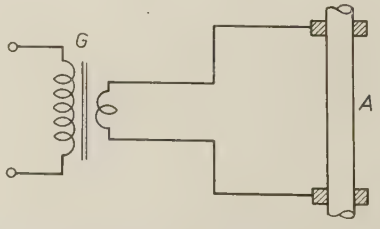

Fig. 2. Heating is provided by passing the secondary current of a transformer (max. 2500 A) through the wall of a section of pipe forming part of the reactor circuit. The transformer *G* is connected to the pipe *A* by flexible copper strip brazed to copper blocks.

The heat produced by this element is regulated by varying the primary current of the transformer between 0 and 32 A. The primary current is passed for this purpose through an antiparallel arrangement of two PL 260 thyratrons, whose moment of ignition varies with the temperature of the fluid (*fig. 3*).

The thyratrons are ignited by a voltage pulse applied to their grids; this is superimposed on a permanent grid bias that keeps the valves cut-off in the absence of a pulse. As the anode voltage is

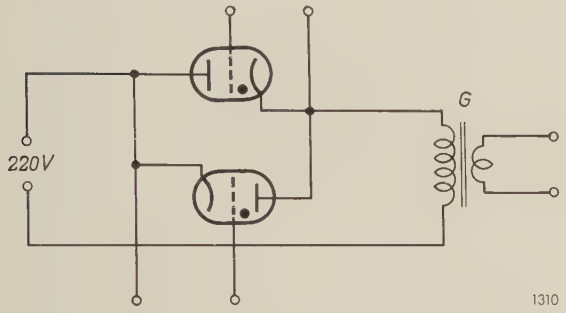

Fig. 3. Primary circuit of heater transformer with antiparallel thyratrons for regulating the current. When the heat output has the correct value, the thyratrons ignite at the moment when their anode voltage is maximum. If the fluid becomes too hot, the moment of ignition occurs later and the current drops; if the fluid becomes too cold, the moment of ignition occurs earlier and the current rises.

sinusoidal and the ignition potential depends linearly on the grid voltage, the "permanent" grid bias can simply be an alternating voltage in antiphase with the mains voltage (*fig. 4*). The method of ignition described makes it possible for the valves to be ignited also in the second half of the time-interval in which the anode voltage is positive, so that the current can also have values lower than half the maximum and even drop practically to zero [3]).

The circuit that supplies the pulse, and which we shall term the ignition circuit, is shown in *fig. 5*. The installation contains two such circuits, one for each thyratron (fig. 3). The heart of each ignition circuit is another thyratron (PL 2 D 21), the anode voltage for which is obtained from the mains via a transformer, and is thus likewise an alternating voltage. The anode current produced upon ignition flows through the primary of the output transformer T_2. As the output voltage of this transformer is proportional to the time derivative of the anode current, T_2 gives a relatively high voltage pulse at the moment this tube ignites.

Of course, the moment at which the thyratrons in the ignition circuits start to conduct must also be

[3]) An example of an earlier application of pulse-controlled thyratrons is given in Philips tech. Rev. **12**, 83-93, 1950/51.

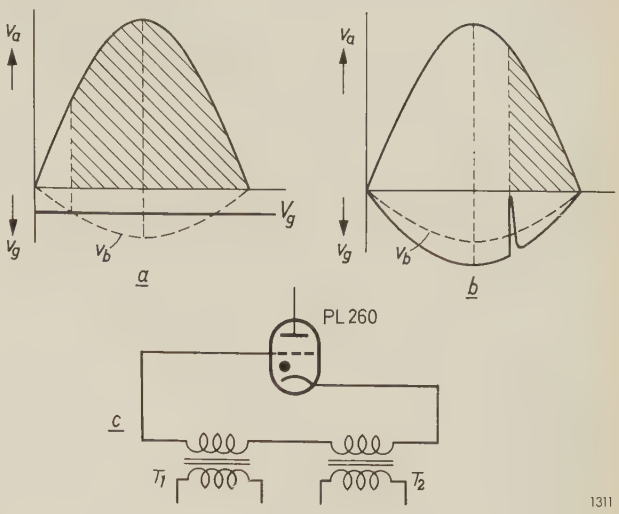

Fig. 4. *a*) If the anode voltage v_a of a thyratron varies sinusoidally, so does the value v_b of the (negative) grid voltage which is just sufficient to prevent ignition. Where v_g has a constant value V_g which is smaller than the maximum value of v_b, the thyratron ignites at the moment that V_g is less negative than v_b and remains conductive for the remainder of the half-cycle (of mains frequency). Ignition in the second half of this time-interval is impossible with a fixed grid voltage. *b*) Ignition in the second half of a half-cycle is possible if v_g consists of a sinusoidal voltage greater than v_b (and in antiphase with v_a) with a pulse superimposed on it. *c*) The sinusoidal component of v_g and the pulse are fed to the grid via separate transformers T_1 and T_2.

capable of displacement within a whole half-cycle of the mains voltage. This is achieved by making their grid voltage a composite one consisting of:

a) an alternating voltage v_1 lagging 90° in phase behind the anode voltage v_a;

b) a variable direct voltage V_2;

c) an alternating voltage v_i whose amplitude V_i is proportional to the difference between the measured and the desired temperature of the

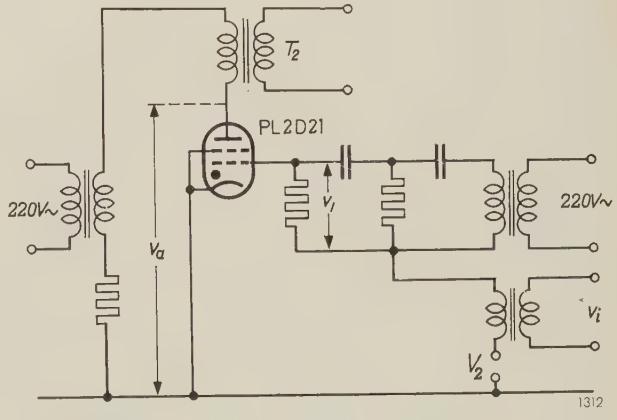

Fig. 5. Diagram of one of the two ignition circuits. v_1 alternating voltage lagging 90° in phase behind v_a. v_i alternating voltage whose amplitude varies with the temperature of the suspension and which is either in phase or in antiphase with v_a, depending on whether this temperature is too high or too low. By varying V_2, a direct voltage, it is possible, when the amplitude of v_i is zero, to make the tube ignite at the precise moment when v_a is maximum.

suspension. This voltage is in phase or in antiphase with v_a, according to whether the suspension is too cold or too hot, and is derived from a resistance thermometer.

Fig. 6 shows how v_g varies with time and how the variation of V_i can shift the moment at which the pulse occurs over almost the whole time-interval of a half-cycle of the mains voltage. The direct voltage V_2 serves for making the moment of ignition when $V_i = 0$, that is when temperature equilibrium has been reached, coincide with the moment at which v_a is maximum. The power

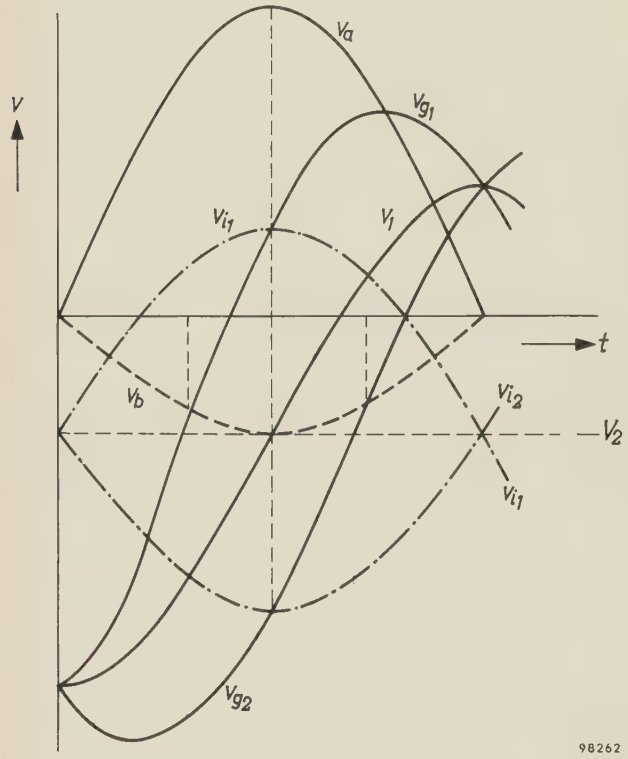

Fig. 6. Components of the thyratron grid voltage in one of the ignition circuits. The voltage v_i is denoted by v_{i1} when the suspension is too cold and by v_{i2} when it is too hot. The curves for v_1, v_{i1} and v_{i2} are drawn about the zero-line $v = V_2$. Curves v_{g1} and v_{g2} represent the time variation of the grid voltage $V_2 + v_1 + v_i$ when v_i has the two waveforms as shown. These waveforms correspond to 0.02 °C too low and 0.02 °C too high, respectively. Since v_i can have a much larger amplitude than represented here, the point where the v_g and the v_b curves intersect can be shifted over almost the entire time-interval of a half-cycle.

dissipated in the heater element, and the average current, then have half their maximum values. It can be shown that the power delivered by the heater to the suspension depends, over a considerable temperature range, more or less linearly on the temperature difference to be corrected (*fig. 7*).

The resistance thermometer mentioned is connected conventionally in a Wheatstone bridge (*fig. 8*). The temperature element itself is a plat-

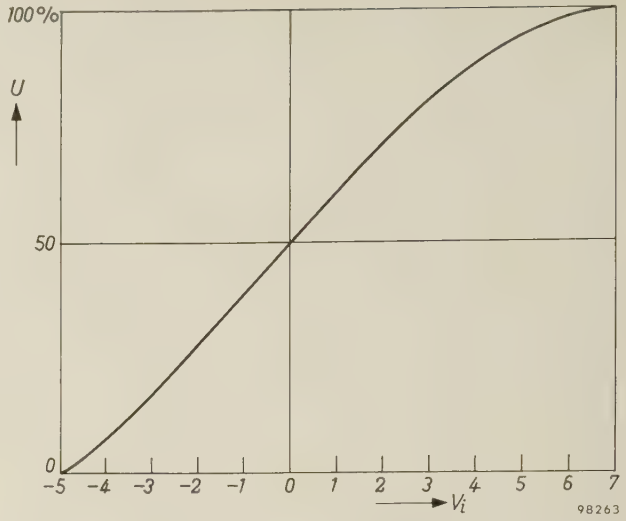

Fig. 7. The power U delivered by the heater varies linearly, over a large part of the control range, with the temperature deviation of the suspension, i.e. with v_i. The value of U is given as a percentage of the maximum; the units along the horizontal axis are arbitrary.

inum wire R_T, whose resistance at 20 °C is about 100 Ω. The bridge is fed by a 10 V alternating voltage of mains frequency. The comparison resistance R_R is variable in 20 steps each corresponding to 4 °C, and further into 20 steps each corresponding to 0.2 °C. The error voltage appearing between a and b, representing the temperature deviation from the desired value, is about 1 mV per 0.1 °C. This voltage is too small to serve as v_i (figs. 5 and 6) and is therefore considerably amplified before being applied to the ignition circuits. The amplification is such that a deviation of 0.05 °C from the desired temperature causes the moment at which the ignition circuit delivers a pulse to shift almost to the beginning or to the end of the half-cycle concerned, thus switching the heater fully on or off, depending on whether the suspension is too cold or too hot.

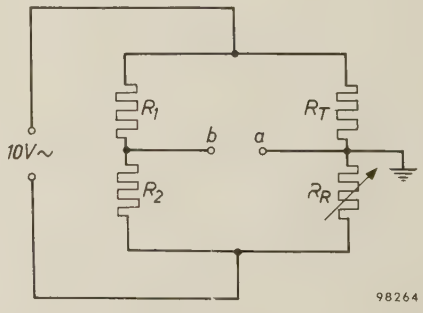

Fig. 8. Wheatstone bridge circuit for resistance thermometer. R_T platinum wire in thermal contact with the suspension. R_R variable comparison resistor. R_1 and R_2 fixed resistors. The voltage between a and b is amplified and used (as v_i) to control the ignition circuits. R_R can be varied in 20 steps corresponding to 4 °C each, and in 20 steps corresponding to 0.2 °C each.

The amplifier is so designed that, even during the running-up period prior to a reactor experiment, when there is a big difference between the actual and the desired temperature (and hence a relatively high alternating voltage between *a* and *b*), the output signal always remains balanced. Thus, the contributions made by the two PL 260 thyratrons (fig. 3) to the primary transformer current are equal under all conditions. Any asymmetry in this current (i.e. the presence of a D.C. component) could seriously damage the transformer.

A block diagram of the whole control system is given in *fig. 9*.

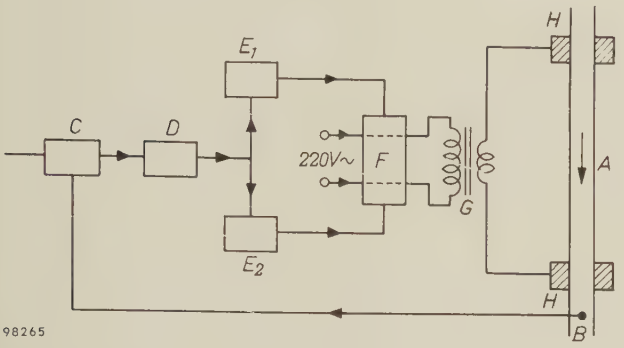

Fig. 9. Block diagram of temperature control system. *A* heater element (section of pipeline). *B* platinum resistance thermometer. *C* Wheatstone bridge, of which *B* is an integral part. *D* amplifier which produces from the bridge voltage a signal capable of driving the ignition circuits E_1 and E_2. *F* regulator of primary transformer current (see fig. 3). *G* heater transformer. *H* connections of transformer secondary to heater element.

Setting the temperature

The first step in setting the temperature of the suspension is to adjust the comparison resistance in the electrical thermometer (R_R in fig. 8) to the value that corresponds to the desired temperature T, and then to switch-on the pump and the control apparatus. The coolant valve remains closed or is only slightly opened. Since the bridge is initially far from balanced, the heater delivers its maximum power. The heat supplied is then about 12 kW (5 kW from the heater and about 7 kW from the pump). As the fluid warms up at the rate of approximately 2 °C per minute, the desired temperature is quite quickly reached. As soon as it is exceeded by 0.05 °C, the heater is automatically switched off (see above). This can be observed on the control panel. The heat production will generally still be excessive, but the rate at which the temperature now rises is evidently greatly reduced (to less than 1 °C/min). Consequently there is ample time to open the coolant valve until the heat extraction reaches, say, 6 kW. The temperature then drops slowly. As soon as it falls below $T + 0.05$ °C, the regulator comes into operation and the temperature is stabilized somewhere in the region from $(T + 0.05)$ to $(T - 0.05)$. The exact value of the equilibrium temperature is determined by the extent to which the coolant valve is opened. The regulator can be set to the middle of the control range by adjusting the opening of the valve while watching the reading on a meter that indicates the power delivered by the heater. This being done, the heater can correct variations of $2\frac{1}{2}$ kW in the coolant or pump power, such that the resulting variations in the suspension temperature are reduced to less than 0.05 °C.

Properties of the control system

We shall now consider the extent to which the system reduces a disturbance and whether the system is stable. To answer both these questions we must know the magnitude of the total gain $A(\omega)$ in the control loop. By this is meant the amplification which a sinusoidal signal of angular frequency ω undergoes after passing successively through all elements of the control loop. In order to determine the function $A(\omega)$ we shall have to cut the loop open somewhere. If all elements are linear, it is immaterial where we do this. Furthermore we must know the way in which the phase shift φ between the input and output signal of the cut-open loop varies with the frequency of the input signal. In short, we need the frequency response (amplitude and phase characteristics) of the open loop.

Fig. 10a and *b* show these characteristics for the system described here. The relation between the gain A and the phase shift φ is represented in a Nyquist diagram as in fig. 10*c*. The length of the line from the origin to a certain point of the diagram is equal to the gain obtained at the frequency in question, and the angle between this line and the axis is equal to φ. The gain is therefore represented in this diagram by a vector.

The vector P by which a control system reduces an incoming periodic disturbance is equal to the absolute value of the vector sum of the vector just referred to, for the frequency of the disturbance signal, and the negative unit vector. Its magnitude, then, can be easily found graphically from the length of the line joining the relevant point of the Nyquist diagram to the point —1 on the axis. At frequencies where $\varphi \approx 0$ the vector sum becomes the arithmetic sum [4]). We can deduce from fig. 10*a* that P is here equal to eight (seven plus one) at such frequencies. *Fig. 11* shows how the reduction factor varies with increasing frequency. For disturbances having an

[4]) The degree to which periodic disturbances are reduced is sometimes expressed as the *deviation ratio* $1/P$.

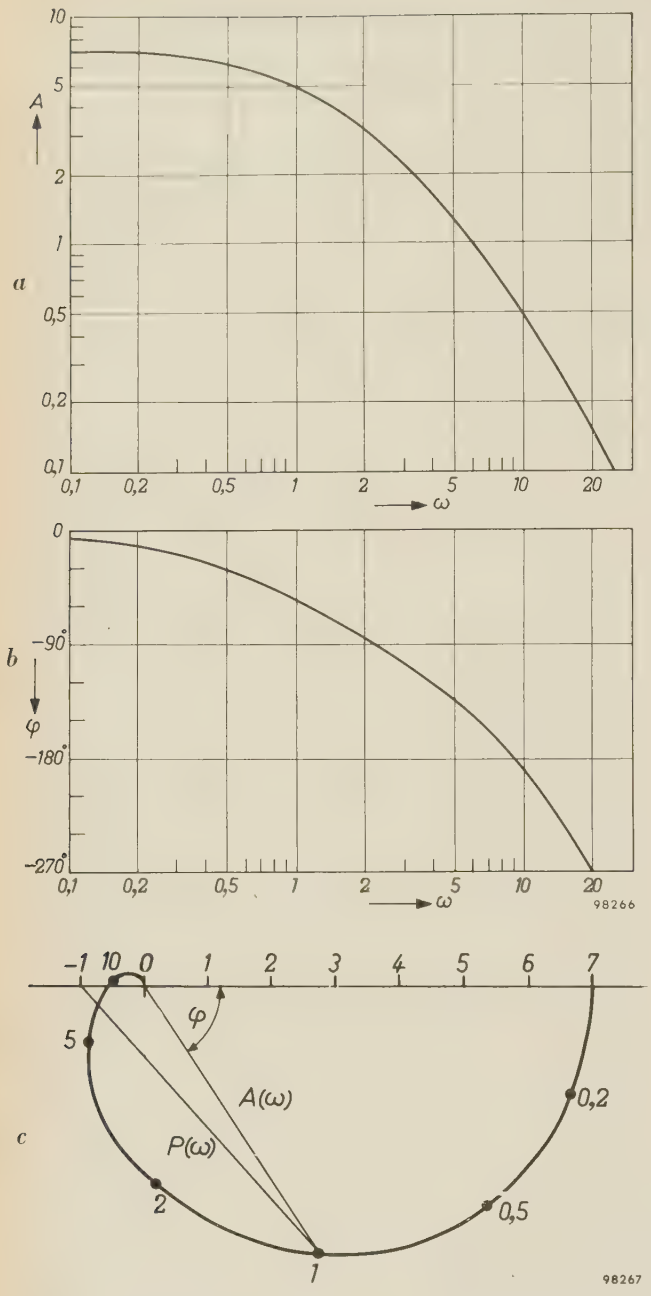

Fig. 10. Frequency-response curves of opened control loop.
a) Amplitude characteristic.
b) Phase characteristic. At very low frequencies the gain is about 7. At the angular frequency ω where the phase shift φ is 180°, the gain is less than unity.
c) Nyquist diagram of temperature control system. The figures around the curve indicate the angular frequency to which the points marked correspond. The distance from these points to the origin is equal to the gain obtained at that frequency; φ is the phase shift. The curve does not enclose the point −1 on the axis (cf. fig. 10*a* and *b*); this implies that the system is stable. The length of the line joining a point on the curve to the point −1 gives the value of the reduction factor $P(\omega)$.

angular frequency between 0 and $^1/_2$ (i.e. $\sim {}^1/_{12}$ c/s) it is seen that P has approximately the value 8. At $\omega = 1.5$ (i.e. $\sim {}^1/_4$ c/s) the reduction factor P has dropped by half. Since, as mentioned, the disturbances occurring in practice are very slow-moving, this "bandwidth" of the control system is entirely adequate.

With regard to stability, fig. 10 shows that the gain is less than unity for the frequency at which φ has increased to 180° — i.e., at which the negative feedback in the loop has changed to positive feedback. From the fact that the Nyquist diagram does not "contain" the point −1, it may be concluded that the control system is indeed stable [5]).

It can also be seen that an appreciable increase in gain, and hence in P, is not possible without endangering the stability. In any case, a higher reduction factor is not needed. A change of no less than 1 kW in the coolant or pump power corresponds to a temperature change, without control, of about $^1/_4$ °C, and with control to a temperature change of only $^1/_{30}$ °C.

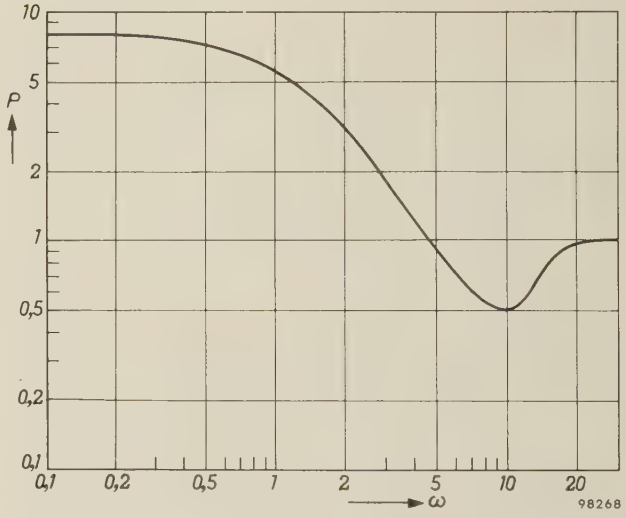

Fig. 11. The factor P, by which periodic disturbances are reduced, as a function of the angular frequency ω of the disturbance (assumed to be sinusoidal).

Measuring the average concentration of the suspension in the reactor vessel

In investigating the properties of a suspension-type reactor, one of the things to ascertain is the relation between the concentration of the suspension and the reactivity, which varies with the concentration in a very marked way. It is therefore

[5]) For complex control systems the stability criterion as formulated here is over-simplified, but for relatively straightforward systems, like the present one, it is adequate. The stability problem is treated in detail in G. S. Brown and D. P. Campbell, Principles of servomechanisms, Wiley & Sons, New York 1948, and in G. J. Thaler and R. G. Brown, Servomechanism analysis, McGraw-Hill, New York 1953.

Editor's note: A derivation of the formulae from which figures 10 and 11 are obtained will be given in a forthcoming article in this journal, dealing with control theory.

necessary to measure this concentration in the reactor vessel as accurately as possible. Unfortunately this cannot be calculated from the quantities of solid particles and liquid contained in the whole reactor circuit. Since a suspension settles, the concentration in a section of pipeline in which the liquid flows upwards will be greater than elsewhere. If the flow rate in such a section is so slow as to equal the rate at which the particles settle (with respect to the liquid), all solid particles will ultimately accumulate in that one section. In the reactor vessel, where the flow rate is slow because of the relatively large diameter, this accumulation effect is clearly perceptible. To determine the concentration in the reactor it is therefore necessary to adopt a method that measures solely the contents of the vessel.

We shall deal here with two methods developed for this purpose. Only one of them is universally applicable. The other, which we shall discuss first, can be used in only one of the two types of reactor vessel appropriate for a suspension reactor. The shape of these two types is dictated by the behaviour of the suspension; in unsuitably shaped vessels the suspension settles on to parts of the walls and there may be considerable differences in concentration from one region to another. Experiments have shown that the suspended particles are most uniformly distributed over the volume and do not settle locally on the walls if the reactor vessel has roughly the shape represented in *fig. 12a*, which, for convenience, we shall call cylindrical. The fluid enters the vessel at the bottom, where rotary movement is imparted to it by the vanes *1*, and leaves at the top, where flow-straightener vanes *2* eliminate the rotary movement. The second type, which we shall call spherical, is shown in fig. 12*b*. This has certain constructional advantages, and the powerful turbulence of the fluid removes the need for special measures to prevent settling of the particles on the walls. The distribution of particles over the volume, however, is not so uniform as in the cylindrical vessel.

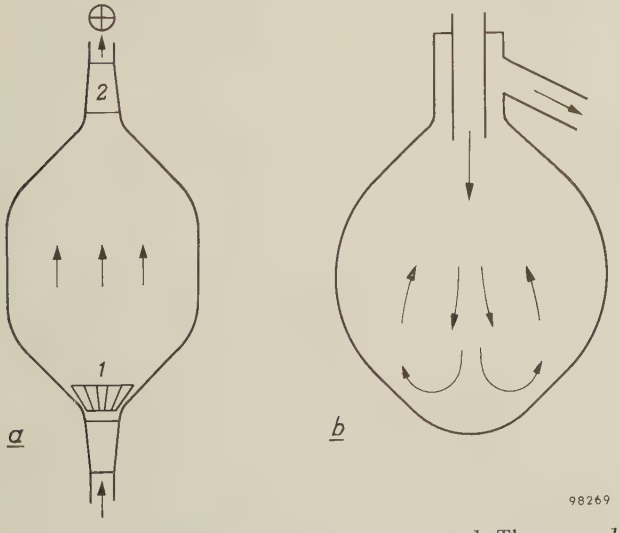

Fig. 12. *a*) "Cylindrical" type of reactor vessel. The vanes *1* impart to the influent a rotary motion, which is eliminated in the effluent by the vanes *2*.
b) "Spherical" type of reactor vessel. The arrows indicate the direction of fluid flow.

An investigation of this uniformity was made by measuring the concentration at various places by means of the absorption of light. The principle of this method is represented schematically in *fig. 13*. Since UO_2 particles absorb virtually all the light, even when the concentration is low and the slit narrow, the measurements were carried out on a suspension of grains of sand of suitable size. *Fig. 14* shows the result of two series of measurements at various heights in a cylindrical vessel.

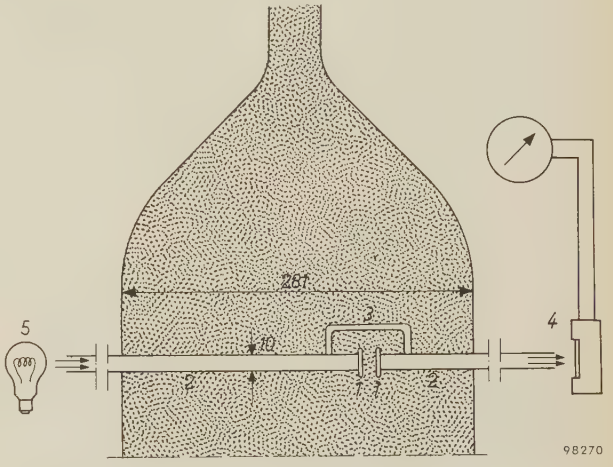

Fig. 13. The local concentration of a (non-radioactive) suspension in the reactor vessel was measured at various heights by means of light-absorption. The windows *1* fitted in the tubes *2* are kept a constant distance apart by brackets *3*. The whole device can be shifted lengthwise. The photocell *4*, connected to a galvanometer, measures the extent to which the light from the incandescent lamp *5* is absorbed.

The direct method

Both methods of measuring the average concentration in the reactor vessel are based on the law that the difference in hydrostatic pressure of two points at unequal heights is proportional to the density of the liquid. The simpler method is illustrated in *fig. 15*. Above and below the reactor vessel, branch arms are led out and connected to a differential manometer. As there are no suspension particles in the manometer tubes — the liquid is at rest and the few particles that do get through will in any case soon settle — the pressure difference is found from the product of the difference in height δh of the liquid levels in both arms and the density ϱ_l of the liquid. Assuming that the flow of the suspension makes no contribution to the

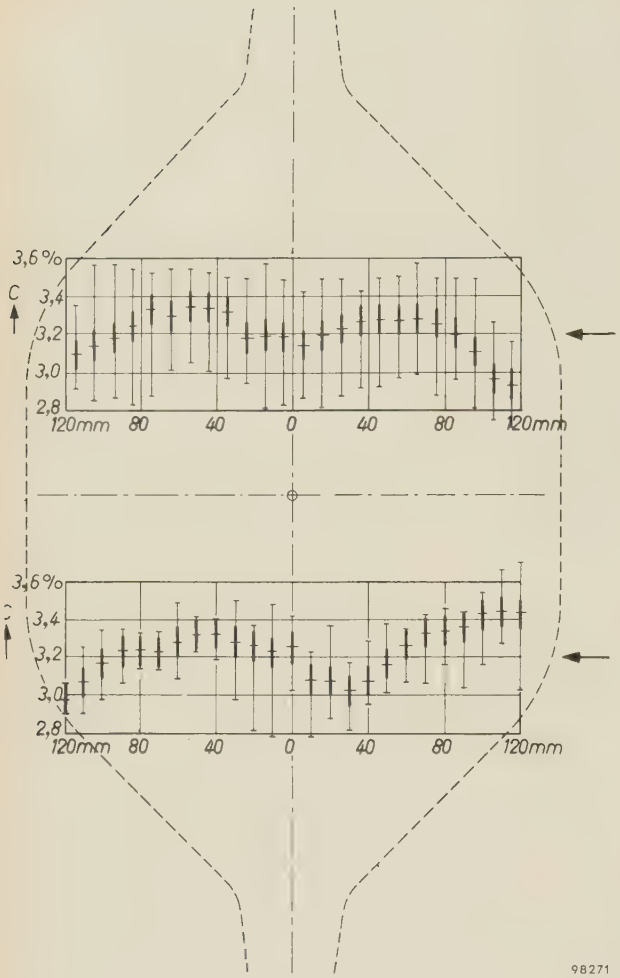

Fig. 14. The concentration, in percentage by volume, of solid particles at various places in the cylindrical reactor vessel (dashed line). The arrows (right) indicate the heights at which the measurements were made. The length of the thick vertical strips gives the standard deviation, the horizontal strips represent the mean values observed. The ends of the thin vertical strips denote the maximum amplitude of the fastest fluctuations followed by the galvanometer (response time 0.5 sec). It is thus possible that fluctuations of even shorter duration and greater amplitude occurred, but these are presumably of no nuclear-physical importance.

pressure difference, then the latter must be equal to $H \times C(\varrho_s - \varrho_l)/100$, where H is the vertical distance between the two manometer connections (fig. 15), C is the concentration of the suspension in % volume and ϱ_s is the density of the solid particles suspended in the liquid. Equating both expressions for the pressure difference makes it possible to find C.

For the maximum value of C, δh is only about 10 cm. Consequently, if a liquid manometer as in fig. 15 is used, its accuracy, which is not very high, will determine the relative error in the result of the measurement. In reality, therefore, the pressure difference is measured with an electrical instrument specially designed for the purpose, viz. a diaphragm-type differential pressure transducer. The sensitivity and very high stability of this instrument (both as regards its zero point and calibration) make it possible to measure pressure difference with a high degree of accuracy [6]).

In general, the flow of the suspension will of course make some contribution to the measured pressure difference. In turbulent flow this contribution is approximately proportional to ϱv^2, where ϱ is the density of the suspension and v is the flow velocity of the liquid. The validity of this relation suggested the means of largely compensating for the disturbance due to flow. If a liquid flows through a pipe in which there is a constriction, the pressure on the pipe wall at the constriction is

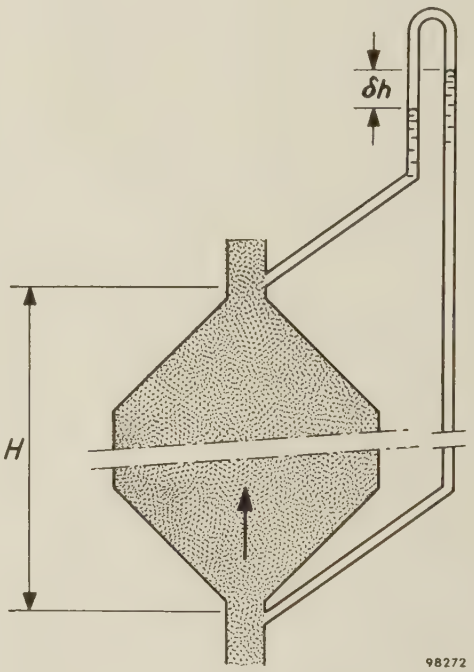

Fig. 15. Principle of the method of measuring the average concentration of the suspension in the vessel from the hydrostatic pressure difference. The liquid in the manometer arms contains no UO_2 particles.

lower than elsewhere, and by an amount that is likewise proportional to ϱv^2. Thus, by applying the upper connection of the manometer to an appropriate point on the reactor vessel — i.e. to a point where the diameter is larger — instead of to the outlet pipe, it was possible to offset the one effect by the other and so to reduce substantially the correction necessary on the manometer reading. The magnitude of the remaining correction was determined by passing the pure liquid through the reactor circuit and measuring the pressure differences at

[6]) This instrument was developed under the direction of J. A. H. Kersten (R.C.N.-KEMA team). It operates on the same principle as commercially available differential pressure pick-ups.

various rates of flow. *Fig. 16* shows a scale drawing of the cylindrical reactor vessel employed in the subcritical experiments, indicating the position and form of the manometer connections.

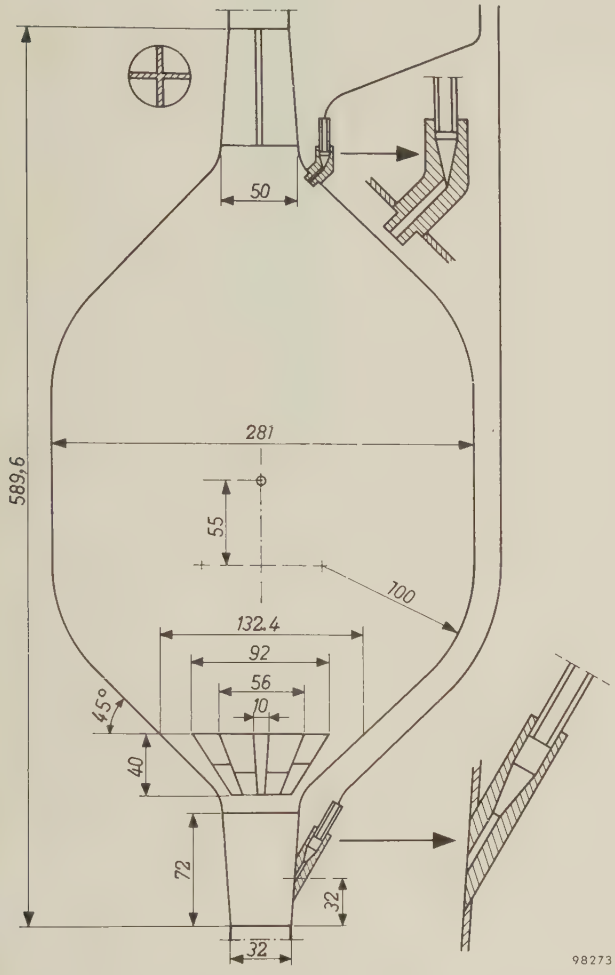

Fig. 16. Scale drawing of cylindrical reactor vessel used in the subcritical experiments, showing the pressure tappings for the differential manometer with which the concentration of the suspension is measured.

The following advantages are associated with the method just described: 1) the equipment required is simple; 2) scarcely any material is introduced on or in the reactor vessel (that would mean extra neutron losses); 3) components that might need repair in the foreseeable future are not positioned close to the reactor vessel (where they would become highly radioactive and therefore impossible or very difficult to repair). A drawback is that the manometer shows some jitter owing to the whirling motion of the liquid in the vessel. That is why this method can only be used for measurements on the cylindrical reactor vessel and not on the spherical type. The violent turbulence in the latter makes the manometer so unsteady that even a moderately accurate reading is quite impossible. In measurements in the cylindrical vessel the uncertainty is about 0.04 % by volume UO_2. Since, under normal conditions, the UO_2 concentration is roughly 2 % by volume, this value corresponds to a relative error of 2%.

The "flow simulator" method

The second method, which is a variant of the first, is distinguished mainly by the comparative steadiness of the manometer and by the fact that the liquid-flow contribution to the pressure difference is practically reduced to zero. This method is accordingly suitable for measurements on a spherical reactor vessel.

The favourable features mentioned are due to the manometer not being connected to the reactor vessel itself or to the reactor circuit, but instead to a device called a "flow simulator", which is in fact a flow shunt connected across the reactor vessel. The form of the simulator can be seen in *fig. 17a*, and fig. 17*b* shows how the device is incorporated

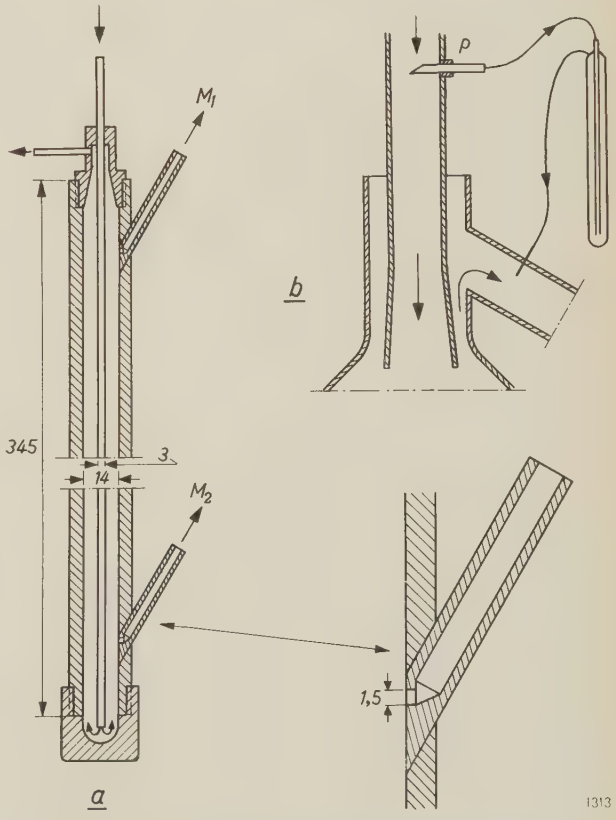

Fig. 17. *a*) Flow simulator. The dimensioning is such that the fluid rises in the wide outer tube at approximately the same velocity as in the cylindrical reactor vessel. The differential manometer is connected at M_1, M_2.
b) Simulator shunted across reactor vessel. For the orientation shown of the pipe *p*, where the supply line of the simulator joins the reactor circuit, the meter indication is proportional to the average concentration in the vessel and also (within a certain range) independent of the flow rate. At other orientations of *p* this is not so, owing to the momentum of the larger UO_2 particles at the mouth of the pipe.

in the reactor system. The simulator line is connected to the reactor circuit in front of and behind the reactor vessel. The fluid enters the simulator through the narrow inner tube and then rises in the outer tube, to which the manometer leads are connected. The flow velocity in the outer tube is very low, so that the pressure difference it causes is extremely small. Moreover the flow is very steady, and so does not unsettle the manometer. The length and cross-section of the simulator tube are chosen so that the fluid rises at the same rate as in the reactor vessel. The effect of the flow rate on the concentration in the reactor vessel and simulator is the same and there is thus a proportional relation between the concentration measured on the simulator and that of the suspension in the vessel.

An incidental advantage of the simulator method of measurement is that the vertical distance between the manometer connections — i.e. the sensitivity of the concentration meter — can if necessary be made larger than in the first method.

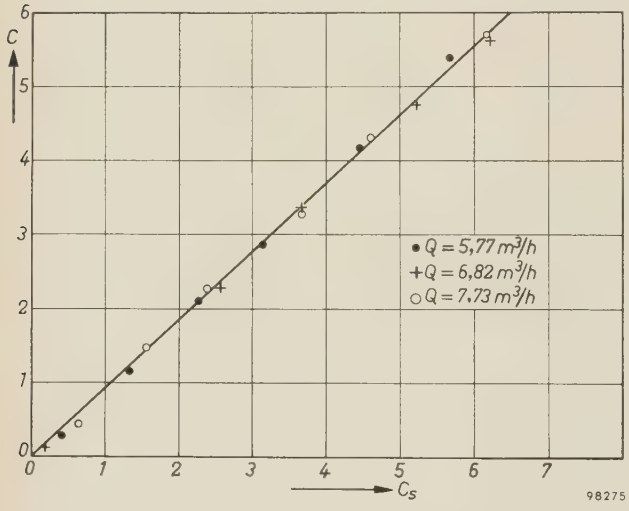

Fig. 18. Calibration of the simulator concentration meter, connected to the spherical reactor vessel. The true concentration (C), determined by weighing the contents of the vessel, is plotted vertically, the concentration (C_s) derived from the meter readings is plotted horizontally. The units on the coordinates are percentages by volume. The meter indication is independent of the flow rate Q in the range of flow rates investigated.

This expedient can only be employed, however, if the concentration does not vary rapidly with time, for it means that the time taken by the suspension to flow through the simulator pipeline will be longer than the time which the fluid through the reactor takes to flow from the first to the second connection point (about 10 sec). Consequently the simulator will not faithfully follow the variation with time of a rapid change of concentration in the reactor vessel.

Fig. 18 shows a result of an investigation into the behaviour of a concentration meter employing a simulator. It can be seen that the indication is admirably proportional to the concentration, and independent of the flow rate of the suspension (at least within the range of flow rates investigated). It also appears, however, that the indication is too high by a constant factor. For absolute measurements this factor must be determined by calibration, but relative changes of concentration can be measured with a good degree of accuracy without calibration.

In the reactor experiments now in progress the reactor vessel is of the cylindrical type. The concentration can be measured by either of the two methods described, although here too the simulator method has proved more accurate. In future investigations of a spherical-type vessel this method, as mentioned, will be used exclusively.

During the initial stage of the investigations a third method was used [7]). On one side of the pipeline close to the inlet of the reactor vessel a radioactive source emitting γ rays was mounted, and on the other side of the pipe a radiation detector. The concentration of the passing suspension was determined from the extent to which γ rays were absorbed. A virtue of this method is that it readily allows an absolute calibration to be made. Drawbacks are 1) that the measurement is not made on the vessel itself; 2) that owing to the limited intensity of the source the measurement takes a certain time before the statistical error in the result is sufficiently small, which means that short-lived changes in concentration cannot be measured, or only very inaccurately; and 3) that the method is difficult to use if the suspension itself shows any marked radioactivity. The latter drawback has already disqualified this method for the reactor experiments now in progress. In the early stages, however, it rendered excellent service as a means of checking the two manometric methods described above.

Measuring the flow rate in the reactor circuit

Among the many methods of measuring the quantity of fluid flowing per unit time through a pipe, the two most widely used are probably the *orifice plate* and the *venturi tube* methods. The principle of both methods is explained in *fig. 19*. In

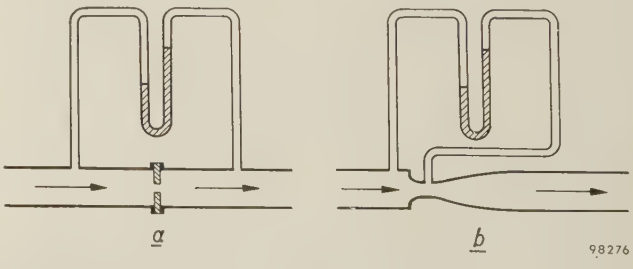

Fig. 19. The two most commonly used methods of flow-rate measurement.
a) The flow rate is determined from the pressure difference over an orifice plate acting as a flow resistance.
b) The flow rate is found from the pressure drop on the tube wall at a point of constriction (venturi tube).

[7]) This method was developed by J. Kalshoven (R.C.N.-KEMA team).

view of the requirements and conditions of the present case, the second method was chosen. A drawing of the somewhat unconventional venturi tube designed for the purpose is shown in *fig. 20*. It will be seen that the diameter at the constriction is not much smaller than elsewhere, so that the tube introduces no appreciable flow resistance into the circuit. Moreover, wear due to abrasion by the suspended particles (in the concentration used) is not severe, and therefore the calibration of the meter remains reliable for a long time. The tube is short, as necessitated by the available space. The holes for the leads to the pressure gauge are arranged so as to prevent them from getting clogged by suspension particles.

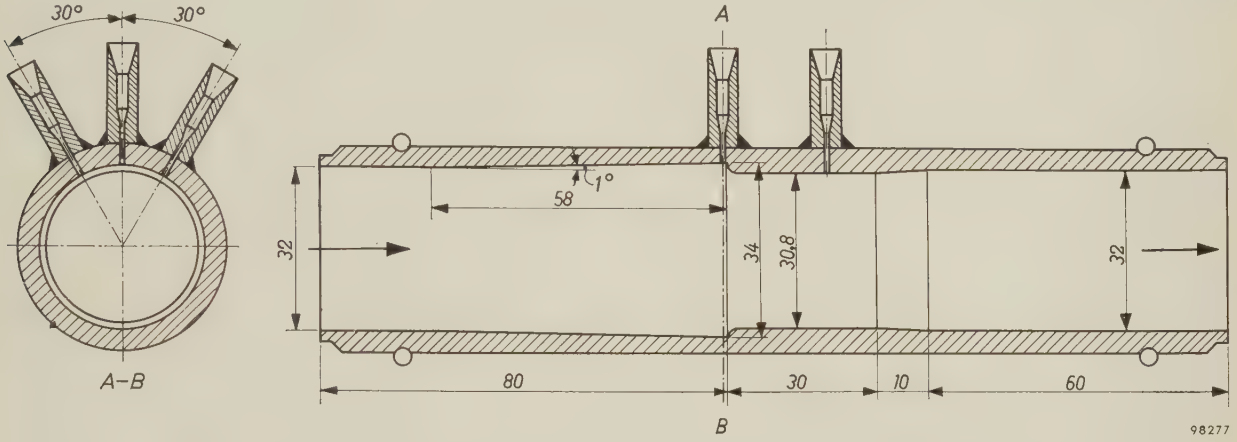

Fig. 20. Scale drawing of venturi tube designed for the reactor. The tube is short and also has a low flow resistance. The outlets of the manometer pipes, which are usually arranged around the tube to obtain an averaging effect, must not in this case depart more than 30° from the vertical, in order to avoid penetration and possible clogging by UO_2 particles.

In designing the tube the aim was to ensure that the pressure difference would be about 50 cm of water at full pumping capacity, i.e. at a delivery of 10.5 m³ per hour. This is in fact the case. Calibration is carried out using clean water and an orifice plate for comparison. The calibration applicable to a suspension is found from that applicable to water by multiplying the meter reading corresponding to a given delivery by the density of the suspension [8]). The pressure difference is measured with a Philips differential pressure transmitter, type PR 6000 F; it is recorded on a type PR 2200 recorder.

Survey of the whole reactor system and instrumentation

We shall now review the whole reactor system together with the other instruments for measuring operating parameters which we have not yet discussed. A layout of the complete installation is given in *fig. 21*. The pipelines and vessels containing the suspension are shown red. Those outlined in black represent the reactor circuit, the others are ancillary lines connecting this circuit to fuel (UO_2) removal and replenishment plant. The primary coolant circuit, containing distilled water, is shown blue, and the secondary, through which mains water flows, is green. The other blue pipeline also contains distilled water which is in addition free from CO_2; this is fed to the pump to "flush" the bearings. Since this water is slightly under pressure, it forces its way slowly in and prevents the penetration or leakage of radioactive suspension particles. The yellow lines contain compressed air (2 atm) which is used, among other things, for emptying the dump tank (see figure) and for the bubble pump, which keeps the water moving in the primary coolant circuit [9]). Not shown is a compressed-air line (4 atm) for operating the valves by remote control.

The flow rate in the reactor vessel can be varied by means of a three-way valve *A* in the reactor circuit. Adjustment of this valve changes the volume flow in the reactor vessel relative to that in the vertical shunt pipe *AB* (shown under the valve). The small volume of water forced into the circuit via the pump-shaft gland can escape via the riser pipe. The flow rate in this pipe is so slow that the UO_2 particles remain at the bottom. Further particulars are given in the caption to the figure.

The principal operating parameters are recorded. These are:

[8]) The pressure difference is proportional to ϱv^2 (see page 128). Strictly speaking the formula is not fully applicable here, since the viscosity of the suspension is not exactly identical with that of pure water. This, however, can be disregarded in the present case (low concentration), a high degree of accuracy not being required.

[9]) The operation of such a pump was recently discussed in this journal in another connection (Philips tech. Rev. **20**, p. 184, 1958/59, No. 7).

1) the temperature of the suspension in the reactor vessel;
2) the flow rate of the fluid in the reactor circuit;
3) the average concentration of the suspension in the reactor vessel;
4) the temperature of the water in the primary coolant circuit on leaving the primary cooler.

The recordings are made with type PR 2200 recorders, installed in the control room. *Fig. 22* shows a typical recorded curve of the concentration (see 3) above).

depicted. The meters mentioned above, together with control valves, are mounted on this panel at their appropriate positions in the diagram (*fig. 23*). Some of the meters are duplicated, the parallel ones being in the room where the reactor is installed. The legend to fig. 21 indicates the meters concerned. The meters for the less important quantities, and those for quantities which need to be measured only very occasionally, are not on the control panel but in the reactor room. These include meters for the p_H and the electrical conductivity of the water in

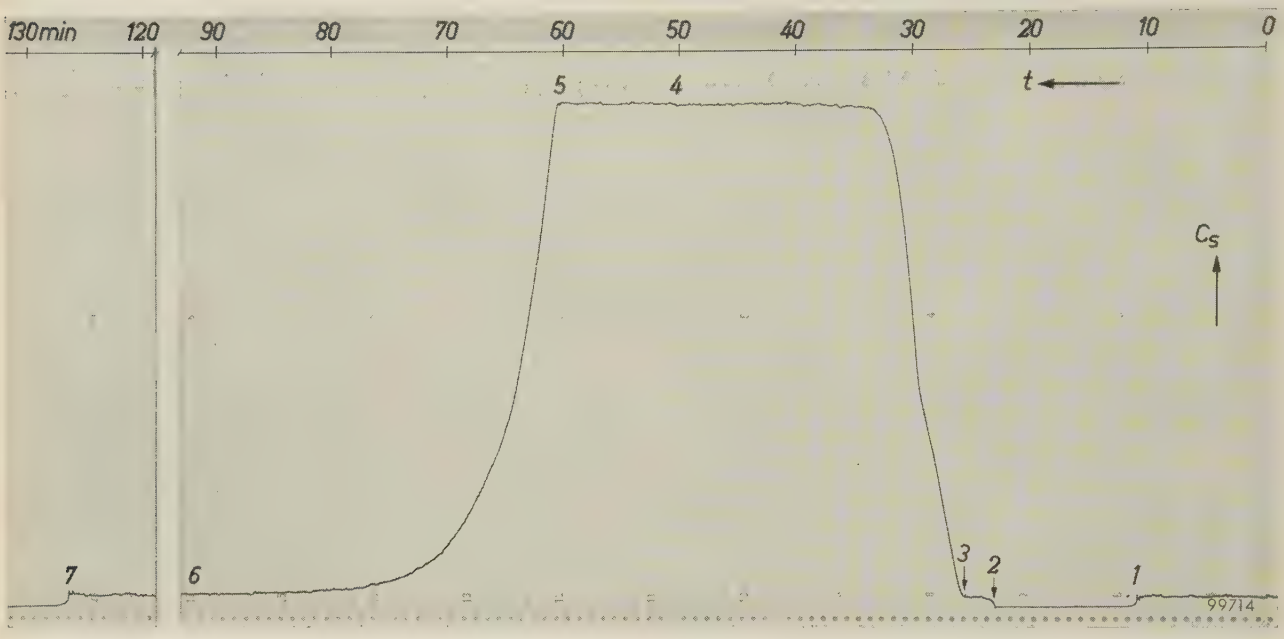

Fig. 22. Recording of the average concentration C_s in the reactor vessel, as a function of time, during various operations. The time scale runs from right to left. Extreme right: pure water is circulating. At *1* the pump was stopped and at *2* re-started: the zero line is unaffected. At *3* UO_2 from the storage vessel was transferred to the reactor vessel; at *4* the concentration has reached an equilibrium value ($\sim$2% by volume). At *5* the cyclone came into operation: at *6* the concentration has fallen to zero. At *7* the pump was once more stopped: the zero line is the same as before. The recording demonstrates the high sensitivity and stability of the differential pressure pick-up used.

The values of most other quantities of importance can be read from meters in the control room. These are:

1) the pressure in the reactor circuit before and after the pump;
2) the temperature of the water entering and leaving the secondary cooler;
3) the flow rate of the secondary coolant;
4) the rate of air flow to the bubble pump;
5) the pressures in the compressed-air lines (4 and 2 atm).

The control room contains a large graphic panel on which the reactor flow sheet as in fig. 21 is

which the UO_2 particles are suspended, a thermometer in the secondary coolant circuit near the input of the primary cooler, level gauges, manometers, etc.

The instruments described in this article have made it possible to make a comprehensive study of the properties of the subcritical reactor system and to monitor the events taking place inside the reactor. Every quantity of importance, or of potential importance, can be measured. Monitoring is not confined to the reactor circuit but extends to the cooling system, so that for example any deterioration of the heat exchange in the coolers as a result

of scale formation can quickly be ascertained. From the experiments carried out so far, much valuable data has been accumulated. Apart from the measurements of the first four quantities mentioned in this section, the measurements on the many secondary quantities have proved of great value.

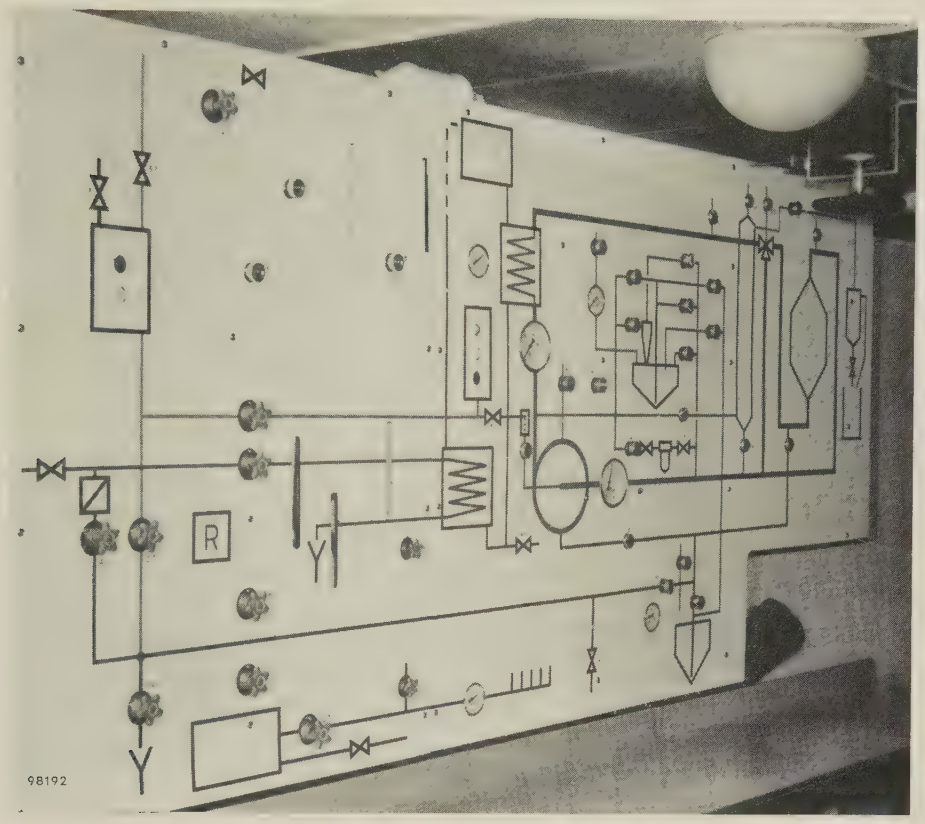

Fig. 23. Graphic panel of the reactor in the control room (cf. fig. 21). The large handwheel (top right) operates the valve that regulates the flow rate through the reactor vessel. Pilot lamps indicate the liquid levels in the storage tank for distilled water and in the pressure-seal water tank. Bottom right is a periscope for reading various meters in the reactor room.

Summary. In experiments on the subcritical suspension reactor at Arnhem it is necessary that the temperature in the reactor vessel should vary by no more than 0.1 °C at any desired value between room temperature and 100 °C. Since the pump that circulates the suspension around the reactor circuit supplies energy to the fluid (about 5 kW), cooling is required at all operating temperatures. As neither the pump energy supplied nor the cooling are perfectly constant, the temperature must be regulated. This is done by means of a heater (a section of pipe in the reactor circuit through which an electric current of up to 2500 A is passed). The heater is controlled by a resistance thermometer and control circuit. The "coolant power" is so adjusted that at the desired temperature the heater delivers half its maximum output (which is 5 kW). The power supplied to the heater is varied by regulating the primary current of the transformer to whose secondary the heater is connected; the regulation is effected by two antiparallel thyratrons through which the primary current passes. These are ignited by a pulse which can be advanced or delayed in both half-cycles of the mains voltage, depending on whether the suspension is too cold or too hot. With this method, the moment of ignition can fall in the second half of a half-cycle of the mains, and thus the current is variable from zero to maximum. Slow variations in temperature are reduced by a factor of 8. Rapid variations cannot occur in practice. The Nyquist diagram of the control system shows that the installation is stable.

The average concentration of the suspension in the reactor vessel is determined from the difference in hydrostatic pressure between two points at different heights. With a vessel of cylindrical shape, in which the fluid flow is relatively steady, the differential pressure gauge can be connected to the reactor circuit itself. A correction must be applied for the pressure difference caused by fluid flow. With a spherical vessel the flow is too turbulent for this method. Here the concentration is measured by connecting the manometer to the wide outer tube of a "flow simulator" shunted across the reactor vessel. The flow rate in this vertical tube is roughly the same as in the reactor vessel, and the concentration in both is affected in the same way by the settling of suspension particles. An additional merit of this method is that the correction for fluid flow is negligible. The flow rate in the reactor circuit is measured with a specially designed venturi tube, having a low flow resistance.

The principal operating parameters are recorded in the control room; many others are indicated on meters. Duplicates of some of these meters are contained in the room where the reactor is installed. Meters for less important or only occasionally measured quantities are not in the control room but only *in situ* on the reactor.

IIIA. THE MONITORING OF LOW NEUTRON FLUX BY MEANS OF FAST PULSE-COUNTING CHANNELS

by J. J. van ZOLINGEN *). 621.039.564.2:621.039.524.46:621.374.32

Introduction

The specific nature of a chain reaction requires that the neutron-flux level in a nuclear reactor should at all times be known. Particularly during the start-up, and even after a shut-down, this quantity and its increase or decrease with time must be under continuous observation.

In a reactor moderated by heavy water the (thermal) neutron flux during start-up is only about 10^{-6} of its rated value, and about 10^{-9} in a graphite-moderated reactor. The neutron-flux measurement must thus cover a range of at least six or nine decades, as the case may be.

Of the other demands to be met by neutron-flux meters the first is a high standard of reliability. There must also be certainty that the indication is not partly caused, or at least not to any significant extent, by the gamma rays always present in a nuclear reactor. Moreover, the neutron-flux detection system must have a rapid response, for in a nuclear reactor the power level can rise extremely rapidly and the automatic safety system or the operating personnel must be able to intervene in good time. Ideally the detection time should be determined only by the statistics of the elementary processes and by the desired degree of accuracy.

There are two ways of measuring neutron flux:

A) by counting the number of pulses which the individual neutrons produce per second in a counter tube, and

B) by measuring the ionization current caused by the neutrons in an ionization chamber.

If both types of neutron detector — counter tube and ionization chamber — have the same volume and gas-filling, they are equally sensitive. Method B has the advantage of simpler equipment, but its use depends on the neutron flux being high enough to cause an accurately measurable ionization current. With method A, on the other hand, the highest neutron flux that can be measured is determined by the rate at which the counting channel is able to count the separate pulses.

The choice between the two methods depends primarily on the intensity of the background (gamma radiation). In the KEMA subcritical reactor the use of a lead shield to attenuate the gamma rays was ruled out owing to lack of space. Method A allows a certain discrimination in respect of pulse amplitude, small pulses caused by gamma rays being electronically blocked and so not counted. With method B the interference from gamma radiation can, if necessary, be compensated by means of a double ionization chamber, both concentric parts of which are sensitive to gamma rays but only one part to neutrons; the difference current of the two parts is then a direct measure of the neutron flux.

Sometimes, however, the latter expedient in method B is not sufficient. The gamma radiation may be relatively so intense that after compensation, imperfect at the best of times, a considerable background remains. This is the case, for example, if the reactor is started up again after a brief shut-down, when there are few neutrons but a high level of residual gamma radiation. In such a case it is necessary to resort to method A, i.e. to count the numbers of discriminated pulses per second, i.e. the *count rate*.

The best solution is often to divide the total measuring range (of six or nine decades) into two ranges that slightly overlap, and to measure low neutron flux by counting pulses, and high neutron flux by measuring the ionization current. This is done in the case of the KEMA subcritical suspension reactor [1]). In this article, IIIA, we shall discuss the pulse-counting method. The ionization-chamber method will be dealt with in article IIIB.

The experiments made with the KEMA subcritical reactor included an investigation of the *fluctuations* of the neutron flux. Since it was not known beforehand what the correlation times of these fluctuations would be, it was necessary to try and observe them in the shortest possible time; an observation is always the average over a certain integration period, and if the latter is long compared with the correlation time, the fluctuations will be largely averaged out again. If, notwithstanding the inevitable statistical fluctuations in the count rate, we wish to detect in a short integration period the fluctuations of the neutron flux, the counting apparatus must be capable of dealing with very high count rates.

*) N.V. KEMA, Arnhem, The Netherlands.

[1]) J. J. Went, Instrumentation for a subcritical homogeneous suspension reactor, I. Reasons behind the choice of a homogeneous suspension reactor, Philips tech. Rev. **21**, 109-121, 1959/60 (No. 4/5).

Suppose we want to detect neutron-flux variations of 1% in 1 second with an accuracy of ± 10%; the apparatus must then be able to handle a count rate of $n = 10^6$ pulses per second. The relative standard deviation from the number n is $\sqrt{n}/n = 10^{-3} = 0.1\%$. There is then a 50% chance that the observation will differ by less than 0.1% from the true average value, and that an observed deviation of 0.1% is a real deviation.

The KEMA reactor is surrounded by a highly effective neutron reflector, consisting of blocks of beryllium oxide and graphite. In order not to detract unduly from the favourable properties of this reflector, only narrow channels are made in it for the neutron detectors (see fig. 5 of article [1])). There is therefore no room for shielding against gamma radiation. Consequently it is only when the neutron flux is fairly high that method B can be used. The measurement by the counting method (A) should extend at least to the value of neutron flux covered by B, which implies a count rate of the order of millions of pulses per second.

Originally the reactor was equipped with a counting system covering five decades and capable of a maximum count rate of 10^5 pulses per second. Later, in the course of 1955, new types of discriminators were designed in the KEMA laboratory. These, in conjunction with a reliable flip-flop circuit of very fast response, resulted in greatly simplified pulse-counting systems with count rates tens of times higher than the old ones and more than a hundred times more sensitive.

A pulse-counting neutron-flux meter

To measure a neutron flux by the pulse-counting method, use is made of a counter tube containing boron, or of a fission counter. (A third type of neutron detector is the scintillation counter; this can deliver pulses at a very high rate, but being delicate and unable to withstand high temperatures it is not suitable for use in a reactor.)

Of the two kinds of counters [2]) the one most used, because of its high sensitivity, is that containing the boron isotope ^{10}B, often as boron trifluoride gas, BF_3. A thermal neutron causes the following nuclear reaction in ^{10}B:

$$^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He + 2.5 \text{ MeV}. \quad . \; . \quad (1)$$

The liberated energy of 2.5 MeV per captured neutron appears as the kinetic energy of the lithium ion and the alpha particle. Both particles consequently leave behind in the gas a trail of electrons and ions, and these charge carriers give rise to a voltage pulse between the tube electrodes.

A fission counter contains a fissile material, e.g. ^{235}U in the form of a solid compound, in which fissions are brought about by thermal neutrons. (A process giving rise to a light particle, a deuteron or — as in (1) — an alpha particle, is not normally called a fission.) The fission fragments are multiply charged heavy ions of high kinetic energy; these ions and the liberated electrons ionize the gas with which the chamber is filled, resulting here too in a voltage pulse at the output terminals. The fission chamber has a very high count rate and its pulses are easily separated from the background, but it is less sensitive than the BF_3 chamber.

The voltage pulses delivered by the BF_3 chamber range in amplitude from about 0.2 to 10 mV. Before these pulses can be separated with sufficient accuracy from the lower-amplitude pulses due to gamma radiation and other background, they must be amplified. The separation takes place in a *discriminator*, a circuit that produces an output pulse only if the amplitude of the input pulse exceeds a certain minimum value (the discrimination threshold). The discriminator output may be applied to a *pulse shaper*, which produces uniform pulses suitable for the actual counting system to handle.

In practice it is desirable to have two counting systems, one logarithmic and the other linear [3]). The logarithmic instrument gives a deflection proportional to the logarithm of the neutron flux Φ. It must have a scale covering many decades; this is of particular importance when the neutron flux changes steeply, as it does during a start-up. The linear instrument (deflection proportional to Φ) provides a more accurate reading.

Another important quantity in a nuclear reactor is the *period* T, which is the reciprocal of the relative flux change per unit time, $(d\Phi/dt)/\Phi$. The voltage output of the $\log \Phi$ meter is differentiated with respect to time and a voltage is then obtained that is inversely proportional to T; this voltage is applied to a meter on which T can be read off directly in seconds [4]).

A block diagram of the apparatus discussed is given in *fig. 1*.

If the count rate is greater than 10^5 pulses per second, various difficulties may arise, mainly in regard to pulse discrimination and shaping.

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[2]) W. Abson, P. G. Salmon and S. Pyrah, The design, performance and use of fission counters, Proc. Instn. Electr. Engrs. **B 105**, 349-356, 1958 (No. 22).
W. Abson, P. G. Salmon and S. Pyrah, Boron trifluoride proportional counters, Proc. Instn. Electr. Engrs. **B 105**, 357-364, 1958 (No. 22).

[3]) The reasons for this are outlined in Philips tech. Rev. **19**, 249, 1957/58.

[4]) See e.g. Philips tech. Rev. **19**, 273, 1957/58.

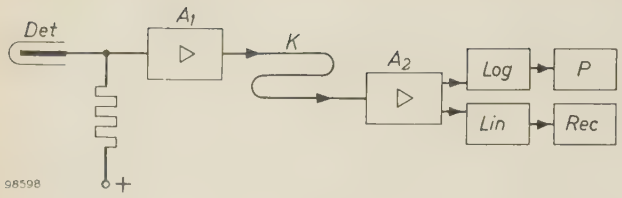

Fig. 1. Block diagram of a two-channel neutron-flux meter and period meter. *Det* neutron detector (e.g. $^{10}BF_3$ counter tube). A_1 preamplifier. *K* cable. A_2 amplifier. *Lin* linear count-rate meter with recorder *Rec*. *Log* logarithmic count-rate meter. *P* period meter.

The "millivolt discriminator"

Drawbacks of conventional discriminators

The pulse-amplitude discriminator hitherto most commonly used is the Schmitt trigger circuit. This is a monostable arrangement of two valves, *I* and *II*; in the quiescent state valve *I* passes current and valve *II* is cut off. A pulse of sufficient amplitude makes *II* conduct and cuts off *I*, after which the circuit returns to its initial state. The minimum pulse amplitude required to trigger the circuit can be preset with a variable biasing voltage.

Drawbacks of this circuit are that the minimum amplitude referred to is fairly large (several volts) and moreover shows a variation of about 5% under low bias conditions. The relative accuracy of the discrimination is therefore not high. It is improved if the biasing voltage is increased to e.g. 100 V, but this calls for correspondingly greater amplification of the pulses. The complication which this involves is considerable, in view of the high gain already required (up to 10^5 times for pulses from a fission chamber) and the wide bandwidth necessary to cope with a high count rate. The result is that it is seldom possible to meet the requirements with less than nine or ten amplifying valves. The fact that the stable state must be rapidly restored after every pulse delivered — otherwise the discrimination threshold would drift — represents an added complication.

The latter is bound up with the "dead time", i.e. the time during which the system after responding to an incoming pulse, is unable to respond to a succeeding pulse [5]). If the dead time is constant, a correction can be applied to allow for the pulses not counted. This is not possible, however, if the dead time varies with the count rate.

These difficulties are largely overcome if a discriminator can be designed whose dead time and discrimination threshold remain constant up to very high count rates, and which is reliably triggered by narrow pulses of the order of 10 mV.

A new discriminator

The fairly low sensitivity of conventional trigger circuits may be explained as follows. In the stable state the cut-off valve has zero transconductance (slope) and hence no gain. The curvature of the I_a/V_g characteristic (i.e. change of slope) is so small that a grid voltage excursion of several volts is needed before the transconductance reaches the value at which the circuit becomes unstable (for this to happen the loop gain is required to be unity). Over this grid-voltage excursion the average transconductance is low and so therefore is the gain; in other words, the valve is not used at the most favourable region of its characteristic.

The situation is improved considerably if a trigger circuit is built in which both valves conduct in the stable state [6]). The principle is illustrated in *fig. 2* (this circuit differs somewhat from that actually used). The input valve *I* is coupled to the output valve *II* via a diode D_1. In the stable state the diode is blocked by the potential drop across resistor R_a (notwithstanding the bias voltage E_1) such that the loop gain (feedback via common cathode load) is less than unity, although both valves are biased to a normal operating point where the transconductance is high. A weak negative pulse on the grid of valve *I* is sufficient, for reasons which we shall

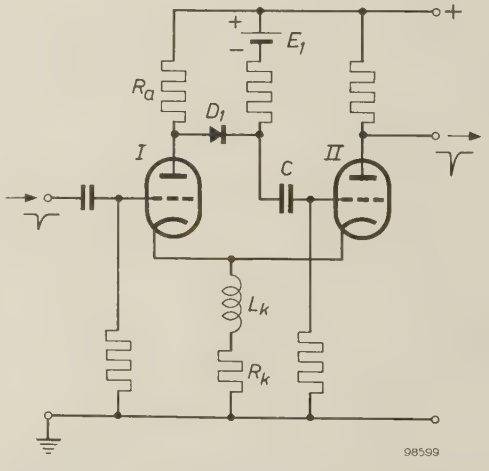

Fig. 2. Principle of "millivolt discriminator". In the quiescent state, valves *I* and *II* are both biased to an operating point where their slope is high, and the diode D_1 is blocked by the voltage drop across the anode resistance R_a, in spite of the biasing voltage E_1. A negative input pulse of sufficient magnitude makes the diode conduct. As a result, valve *I* is temporarily cut off and the current through valve *II* is doubled. The output pulse appears on the anode of valve *II*.

[5]) See e.g. E. J. van Barneveld, Fast counter circuits with decade scaler tubes, Philips tech. Rev. **16**, 360-370, 1954/55.

[6]) J. J. van Zolingen, Gevoelige triggerschakelingen, Ned. T. Natuurk. **23**, 42-55, 1957 (in Dutch).

presently explain, to make the diode conduct to such an extent that the loop gain becomes greater than unity. In valve *I* the current then drops to zero, in valve *II* it becomes twice as high as it was, resulting in a pulse of virtually constant amplitude at the anode of valve *II*.

We shall now examine the process in more detail. A negative pulse of, say, 20 mV on the grid of *I* reduces the anode current of this valve and thus increases its anode voltage. The diode D_1, which was hitherto blocked, then conducts, consequently increasing the grid potential (and hence the cathode potential) of valve *II* via the coupling capacitor *C*. Since the cathodes have a common cathode load, the cathode potential of valve *I* also increases, causing a further drop in the current through this valve. This process, then, leads to a very rapid regenerative cut-off of valve *I*. The cathode inductance L_k tends to keep the current flowing through it at a constant value, so that any increase in the current of valve *II* can occur only at the cost of the current through valve *I*. This effect helps to speed up the change-over. The rise in the current through *II* produces a drop in the anode potential, resulting in a negative voltage pulse at the output.

Since the circuit can be designed to operate reliably with input pulses of only 12 mV, we call it a "millivolt discriminator".

The favourable characteristics of the circuit are due in the first place to the high transconductance at the operating point of both conducting valves, and in the second place to the fact that the diode requires a smaller voltage excursion (*fig. 3*) to make it conduct than a triode or pentode; moreover it is not the input pulse itself that makes the diode conduct, but the pulse amplified by valve *I*.

In the circuit described the diode passes no current in the stable state. Discriminator circuits have been described elsewhere [7]) in which use is also made of a diode, but in the stable state this passes a current that depends on the discrimination level. The biasing of the valves is related to that of the diode, so that in these cases the point of maximum transconductance cannot usually be reached.

Fig. 4 shows the circuit diagram with some details added:

1) The anode load of valve *I* is an inductance L_a of 10 μH in parallel with a damping network consisting of a diode D_2 and a series resistor R_d. The resonant circuit formed by L_a with its stray capacitance is damped by R_d-D_2 such that, when valve *I* is cut off, a positive pulse with a single negative undershoot appears at the anode, as drawn in fig. 4. This waveform minimizes the accumulation of charge of the coupling capacitor *C*.

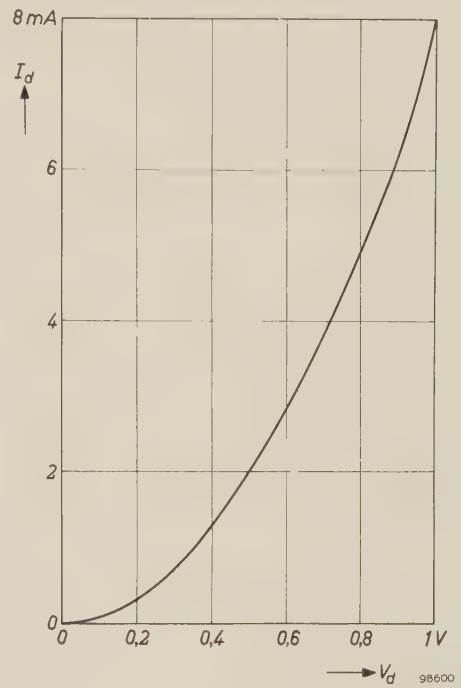

Fig. 3. D.C. characteristic (current I_d as a function of voltage V_d in the forward direction) of germanium diode type OA 85 (D_1 in figs. 2 and 4).

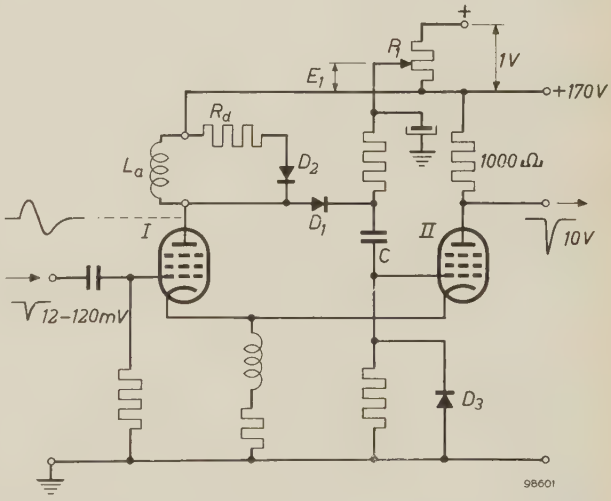

Fig. 4. Circuit diagram of millivolt discriminator, showing more details than fig. 2. Valves *I* and *II* are E 180 F pentodes, D_1 is a germanium diode, type OA 85. The anode load of valve *I* consists of a coil L_a (inductance 10 μH) shunted by a damping resistor R_d in series with a diode D_2. An input pulse of sufficient magnitude (≧ 12 mV) causes the anode voltage of *I* to rise. D_3 is a clamping diode through which any excess charge on the coupling capacitor *C* has a rapid path to earth. Potentiometer P_1 is used for adjusting the biasing voltage E_1 (0-1 V) which blocks D_1; in this way the discrimination threshold can be varied from 12 to 120 mV. The output pulse has an amplitude of 10 V across an anode load of 1000 ohms.

[7]) K. Kandah, A sensitive pulse trigger circuit with a stable threshold, Proc. Instn. Electr. Engrs. **101-II**, 239-247, 1954. S. Barabaschi, C. Cottini and E. Gatti, High sensitivity and accuracy pulse trigger circuit, Nuovo Cimento Ser. X, **2**, 1042-1051, 1955.

2) Any excess charge on C can rapidly leak away through the clamping diode D_3.
3) Since the D.C. voltage drop across L_a is very small, the diode D_1 is blocked in the stable state by the biasing voltage E_1, the polarity of which is opposite to that in fig. 2. E_1 can be varied with the potentiometer P_1, making the discrimination threshold variable from 12 to 120 mV.

The measures mentioned under (1) and (2) give the circuit the desired virtues of a discrimination threshold and a dead time that depend to an almost negligible extent on the count rate. Measurements made with statistically distributed pulses have shown that the circuit possesses a dead time of 1.8×10^{-7} sec $\pm$ 20%. This value remains constant, within the limits of observation errors, up to count rates of 2.5×10^6 pulses per second.

Fig. 5a shows the biasing voltage E_1 measured as a function of the amplitude V_i of the input pulses at which the circuit is just triggered. Except at the lowest point, the deviation from linearity is no more than 2% of the local value. The measurement was made with pulses of the shape illustrated in fig. 5*b*: total pulse-duration 10^{-7} sec, rise time about 1×10^{-8} sec, decay time 4×10^{-8} sec (rise time is defined as the time taken by the pulse to rise from 10% to 90% of its peak amplitude, and decay time as the time taken by the pulse to drop from 90% to 10% of its peak amplitude). The circuit has a large bandwidth, enabling it to deal with pulses of extremely short duration, as follows from the fact that the sensitivity was found to be only 25% lower for pulses of the shape shown in fig. 5*c* (total duration 1.8×10^{-8} sec, rise and decay times 0.75×10^{-8} sec).

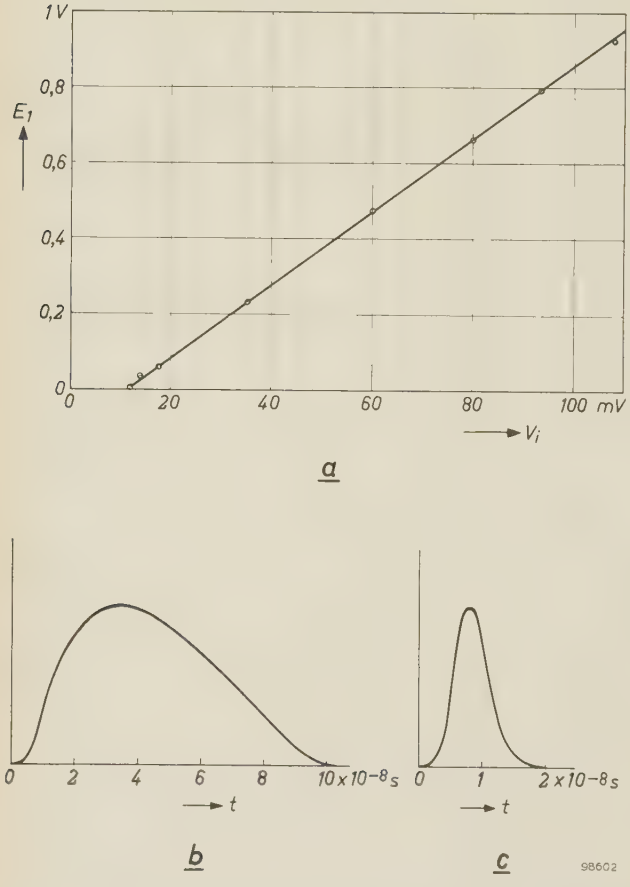

Fig. 5. *a*) Biasing voltage E_1 measured as a function of the threshold amplitude V_i which the input pulses must have in order to trigger the circuit in fig. 4.
b) Shape of the pulses used for the measurement of (*a*).
c) Pulse for which the circuit is only 25% less sensitive.

The large bandwidth and sensitivity are mainly due to the use of high-slope pentodes (type E 180 F) and a low-capacitance diode (germanium diode OA 85). Temperature variations of 18 °C were found to have scarcely any effect on the discrimination threshold.

The output pulses have an amplitude of 10 V across a resistance of 1000 ohms.

Stability of the millivolt discriminator

The stability of the millivolt discriminator was tested by applying to the circuit statistically distributed pulses from a scintillation counter at the mean rate of approximately 2×10^6 per second. The counter consisted of an anthracene crystal mounted on a photomultiplier tube and excited by gamma radiation from a ^{60}Co source. The pulses from the photomultiplier were applied directly to the millivolt discriminator, biased to a discrimination threshold of 30 mV. Repeated measurements were made throughout one week, during which the discrimination threshold referred to corresponded to the pulse height at the steep side of the Compton continuum in the energy spectrum of the electrons liberated by the gamma rays [8]). It was found that the discrimination threshold was stable to within 3%, and this small fluctuation was certainly not entirely due to the discriminator but must have been partly attributable to the photomultiplier, whose gain would not have been constant owing to the temperature variations that occurred.

The count-rate meters

For converting pulses of standard amplitude into a direct current proportional to the neutron flux Φ, or to log Φ, an integrating element is required. For this purpose we use a *pump circuit* (or a series of pump circuits). The waveform of the output voltage of the discriminator discussed above is

[8]) See e.g. J. A. W. van der Does de Bye, The scintillation counter, Philips tech. Rev. **20**, 209-219, 1958/59 (No. 8).

not suitable, however, to be applied to a pump circuit, and it was therefore necessary to include a pulse shaper between these two elements. We shall return to the pulse shaper after we have discussed the pump circuits, having then made clear the requirements to which the pulses must conform.

The basic form of the pump circuit is shown in *fig. 6*. It consists of a "reservoir capacitor" C_1, two diodes D_4 and D_5, and a "buffer capacitor" C_2

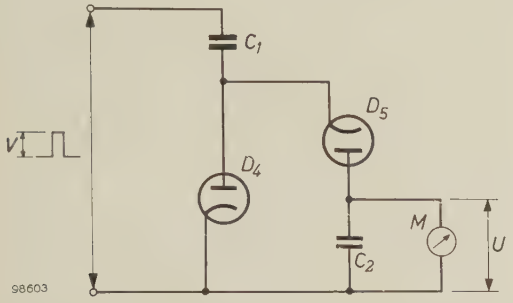

Fig. 6. Principle of pump circuit. C_1 reservoir capacitor. C_2 buffer capacitor. D_4, D_5 diodes. M milliammeter.

across which a meter M is shunted having a resistance R. Positive rectangular pulses of amplitude V are applied to the input at the rate of n per second. Each pulse, provided its duration is long enough, charges C_1 to the voltage V via D_4. At the end of the pulse a charge of magnitude $C_1(V-U)$, where U is the voltage across C_2, passes from C_1 to C_2 via D_5. If the time constant C_2R is large with respect to the period $1/n$ of the pulses, we can regard U as a constant (ripple-free) voltage. The charge supplied per second to C_2 via D_5 is thus $nC_1(V-U)$, and this current is equal in the steady state to the current U/R flowing through the meter. This equality leads to the following expression for the output voltage U:

$$U = \frac{nC_1R}{1+nC_1R}V = \frac{n\tau}{1+n\tau}V, \quad . \; . \quad (2)$$

where τ is the time constant C_1R.

The linear count-rate meter

In order to measure the count rate n on a linear scale, we must have a voltage proportional to n. From (2) we see that the relation between U and n is not a linear one. It is linear to a good approximation however, provided that:

$$n\tau \ll 1, \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

for in this case (2) becomes:

$$U \approx n\tau V \; (\ll V). \quad . \; . \; . \; . \quad (4)$$

If this condition is satisfied, and if also the amplitude V of the input pulses is constant, we can read the neutron flux on a linear scale on the (moving-coil) meter.

The range of count rates in which the linear relationship is valid to a sufficient approximation can be appreciably extended by adding a negative-feedback circuit including a D.C. amplifier, as shown in *fig. 7*. The linearity condition of equation (3) can now be satisfied without the voltages U' and U'' (fig. 7) being small with respect to V. We now have:

$$U = U' + U''$$

and, if the gain of the amplifier is A:

$$U'' = -AU,$$

$$U' = (A+1)U.$$

Thus, U' and U'' have virtually the same magnitude but opposite polarity. At full deflection of the meter, the voltage U required from the integrating circuit is smaller by a factor A than in the circuit of fig. 6, which means that the desired linearity is obtained up to very much higher count rates. The amplitude of the deflection is virtually unaffected by A, provided that $A \gg 1$, e.g. ≈ 500; this is evident since U'', to which the deflection is proportional, is $-U'A/(A+1) \approx -U'$, hence practically independent of A.

The linear count-rate meter in the KEMA reactor is provided with a feedback circuit of this kind.

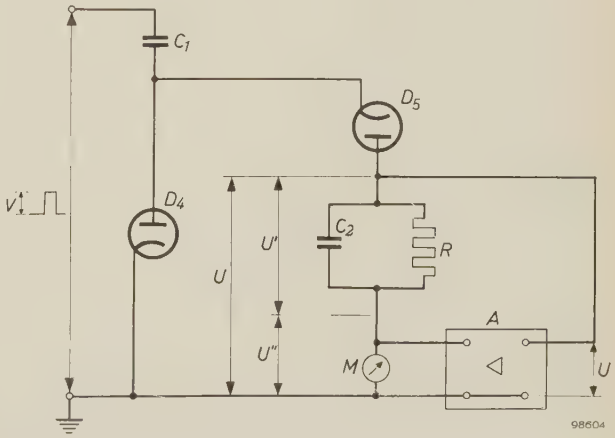

Fig. 7. Pump circuit with negative feedback via a D.C. amplifier A, which increases the range of count rates n over which the deflection of the moving-coil meter M varies linearly with n.

The logarithmic count-rate meter

To obtain a count-rate meter with a logarithmic scale, we make use of a number of pump circuits whose time constants form a geometric progression,

as described by Cooke-Yarborough and Pulsford [9])[10]). If, for example, we take three pump circuits whose time constants are τ_0, $10\tau_0$ and $100\tau_0$, respectively, feed the same pulses to these circuits and add the three output voltages together, we find that the total output voltage increases more or less linearly with the logarithm of the count rate n over a range of about two decades (*fig. 8*). (For reasons of circuitry it is easier to add the output currents than the output voltages; fig. 8 accordingly refers to the currents.) The use of more pump circuits widens the range in which the total current increases approximately linearly with log n.

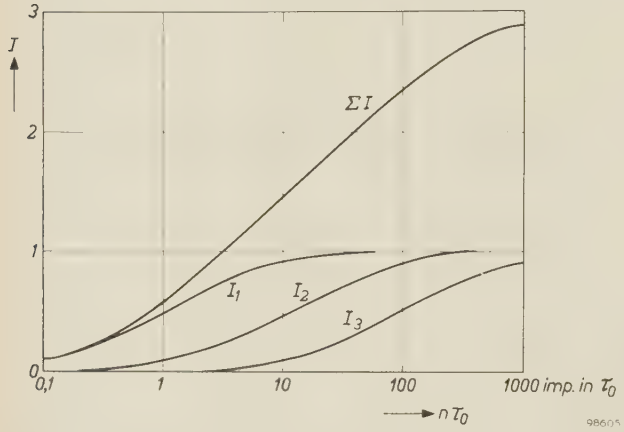

Fig. 8. Curves I_1, I_2 and I_3: output current of pump circuits with time constants τ_0, $10\tau_0$ and $100\tau_0$, as a function of the number of pulses $n\tau_0$ in the time τ_0. The sum ΣI of I_1, I_2 and I_3 varies nearly linearly with log n over about two decades. This range is widened as more pump circuits are connected in parallel.

If τ_r is the time constant of the r^{th} pump circuit, and if the count rate changes from n to an, then the change δU_r in the output voltage of this pump circuit is

$$\delta U_r = \left(\frac{an\tau_r}{1+an\tau_r} - \frac{n\tau_r}{1+n\tau_r}\right) V,$$

where V is again the amplitude of the pulses.

We now consider an infinitely large number of parallel pump circuits [9]), whose output voltages are added together and whose time constants form a geometric progression of ratio k, so that for the r^{th} circuit:

$$\tau_r = \tau_0 k^r.$$

The change δU_0 in the total output voltage is then given by:

$$\delta U_0 = \sum_{r=-\infty}^{r=+\infty} \delta U_r = \sum_{-\infty}^{+\infty} \left(\frac{an\tau_0}{k^{-r}+an\tau_0} - \frac{n\tau_0}{k^{-r}+n\tau_0}\right) V. \qquad (5)$$

The result of this summation, writing $\log k = \lambda$, is:

$$\delta U_0 = \left[\frac{\log a}{\lambda} - \frac{4\pi}{\lambda} \exp\left(\frac{-4\pi^2}{\lambda}\right) \sin\left(\frac{2\pi}{\lambda} \log a\right)\right] V. \quad . \quad . \quad (6)$$

The first term in the right-hand side of (6) yields the required logarithmic relation between δU_0 and a. The second term represents a deviation from the log law but is relatively small (of the order of a fraction of 1%) and recurs periodically from decade to decade (i.e. with the period $\log a$, that is by the same amount for a, ka, k^2a, k^3a, etc.).

Of course, in practice the number of circuits that can be connected in parallel is limited. Deviations will therefore occur from the logarithmic relation both at low and high count rates. It is found, however, that the deviations are appreciably reduced if the pulses fed to the two last pump circuits are given a somewhat larger amplitude, e.g. 15% larger, than the pulses for the other circuits. In this way it has proved possible with six pump circuits to cover a range of five decades, and with eight pump circuits a range of $6\frac{1}{2}$ decades. *Fig. 9* gives the circuit for the latter case, together with the values of the resistances and capacitances. The scale is logarithmic from $n = 1$ to $n = 3\times10^6$ pulses per second, as the calibration curve in *fig. 10* shows. By virtue of these $6\frac{1}{2}$ decades one can readily observe the variation with time of the neutron flux from source level up to the range where the less sensitive neutron-flux meter, which measures the current of an ionization chamber, begins to give a reading (see the following article, IIIB).

In fig. 9 three pump circuits contain a resistor in parallel with the buffer capacitor C_2. This makes it possible to use reservoir capacitors C_1 of greater capacitance than the few picofarads required by equation (6), so reducing the effect of incidental changes in the stray capacitances of the wiring.

The capacitance C_1 in these three pump circuits is made larger than in the others in order to compensate to some extent for the statistically distributed pulses that are not counted, owing e.g. to the finite resolution of the discriminator or of the pulse shaper. In this way the calibration characteristic for statistically distributed pulses is linearized. For periodic pulses, however, the characteristic is somewhat curved at very high repetition frequencies.

The pulse shaper

For linear as well as for logarithmic count-rate meters the pulses are required to be of constant amplitude, irrespective of the characteristics of the valves used in the circuits that produce the pulses, and also at the highest count rates n that occur.

A further requirement in the logarithmic counter is that the pulse duration should increase as n decreases. The smaller n becomes, the more pump

[9]) E. H. Cooke-Yarborough and E. W. Pulsford, An accurate logarithmic counting-rate meter covering a wide range, Proc. Instn. Electr. Engrs. **98-II**, 196-203, 1951.

[10]) For other methods of obtaining a logarithmic scale covering numerous decades, see: F. E. L. ten Haaf, G. Klein and F. J. Schijff, Monitoring, control and safety equipment for a nuclear reactor of the swimming-pool type, II. Further description of certain component units, Philips tech. Rev. **19**, 273-285, 1957/58.

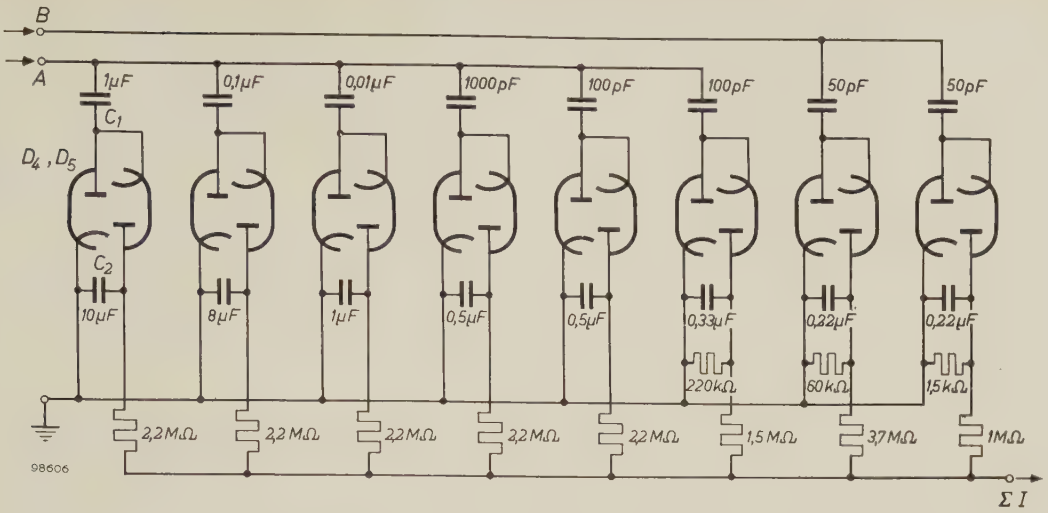

Fig. 9. Parallel arrangement of eight pump circuits. Meaning of C_1, C_2, D_4 and D_5 as in fig. 6. The pulses applied to terminal B are approximately 15% larger than the pulses applied to terminal A. Bottom right is the terminal from which the total output current ΣI is taken. The valves are double diodes, type EAA 91.

circuits in which C_1 has a high capacitance (the circuits on the left in fig. 9) will contribute to the output current, and hence the longer the time needed for these capacitors to be fully charged.

This requirement is certainly not fulfilled by the pulses from the millivolt discriminator discussed above (fig. 4). For this reason, use is made of a bi-stable flip-flop circuit that produces rectangular pulses, the average width of which increases automatically the fewer pulses are supplied to the circuit per second.

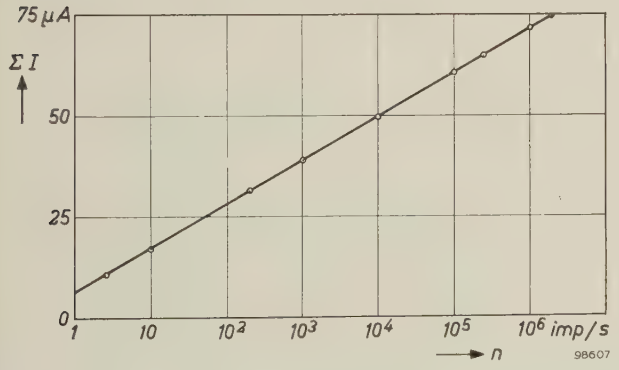

Fig. 10. The output current ΣI of the circuit in fig. 9 as a function of the count rate n. The relation between ΣI and log n is virtually linear over $6\frac{1}{2}$ decades (deviation from linearity nowhere $>10\%$ of the local value).

A flip-flop circuit described by Cooke-Yarborough and Pulsford [9]) delivers pulses that fully meet the requirements as long as n does not exceed a value of approximately 10^5 pulses per second. In our case, however, values of n occur that are more than a factor of 10 higher, and these cannot be handled by the circuit referred to. For this reason an entirely new flip-flop circuit has been designed, capable of particularly rapid operation. This is used in conjunction with an amplitude stabilizer, which in its turn is followed by an output stage; the arrangement is shown in the block diagram in *fig. 11*.

A brief description of these three components is given below.

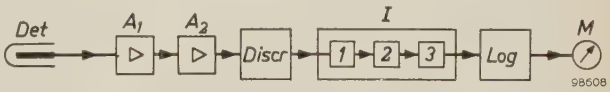

Fig. 11. Between the millivolt discriminator *Discr* and the count-rate meter *Log* a pulse shaper *I* is interposed, consisting of three sections: a fast flip-flop *1*, an amplitude stabilizer *2* and an output stage *3*.

Fast-response flip-flop circuit

The circuit diagram of the pulse shaper, somewhat simplified, is shown in *fig. 12*, section *1* being the flip-flop circuit. The latter is required to have an extremely short dead time (less than 10^{-7} sec) and also to function reliably at count rates as high as several millions per second.

The dead time is shorted by reducing all the time constants involved, in this case the time constant of the anode impedances and that of the coupling networks between the valves. A limit is set to this, however, owing to the fact that if the values of resistance or capacitance are too small, the valves will no longer cut each other off.

Two routing diodes D_{I} and D_{II} are used at the input. These conduct the negative driving pulse to the most sensitive place in the circuit, that is to the grid of the conducting valve. If, however, the count rate exceeds a specific value, the coupling capacitor C_c no longer has sufficient time to dis-

charge. As a result the potential of point Q increases, thereby blocking the routing diodes. This drawback is overcome by clamping the potential of Q with the aid of the diode D_c at a value that can be varied with the potentiometer P_2. This makes it possible to go up to much greater count rates. Fitted with a double triode type E 92 CC and anode resistances of 3300 ohms, the circuit proved capable of handling reliably 15×10^6 regularly-spaced pulses per second [11]).

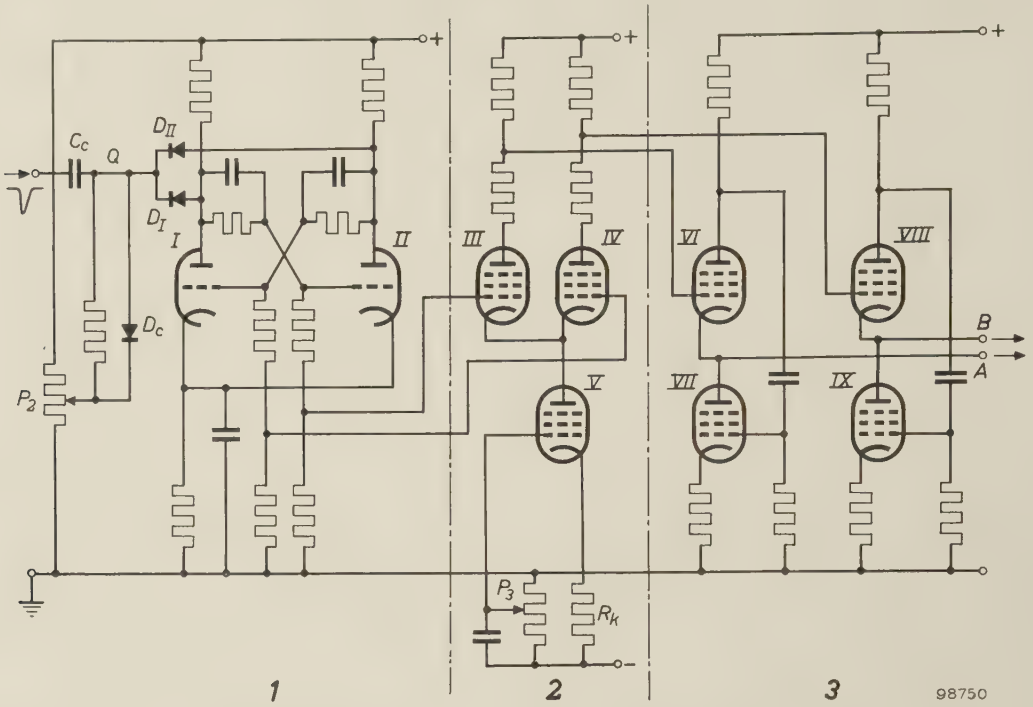

Fig. 12. Circuit diagram of pulse shaper *I* of fig. 11 (somewhat simplified).
Section 1: fast flip-flop. *I-II* double triode E 92 CC; one half conducts while the other is cut off. D_I, D_{II} routing diodes which conduct the incoming negative pulses to the grid of the conducting half of the double triode. (Suppose that *I* is cut off and *II* conducting. In that case *I* has a higher anode voltage than *II*, so that diode D_I is open and diode D_{II} blocked. A negative pulse thus arrives on the anode of *I*, i.e. on the grid of *II* via the associated coupling capacitor.) D_c clamping diode which fixes the potential of point Q at a value that can be varied with potentiometer P_2; this prevents blocking of the routing diodes at very high count rates.
Section 2: amplitude stabilizer. The pulses from the flip-flop circuit drive the pentodes *III* and *IV* (type E 180 F) such that one passes current while the other does not. The pentode *V* (type EF 80) with its cathode resistor R_k acts as a constant current source, the magnitude of the current being adjustable with potentiometer P_3. As a result the voltage pulses tapped from the anode resistors are of constant amplitude.
Section 3: output stage, consisting of two White cathode followers (pentodes *VI-VII* and *VIII-IX*, all type EL 83). This cathode-follower arrangement has the merit of a very low effective input capacitance and output impedance. The output pulses from *VIII-IX* are 15% greater in amplitude than those from *VI-VII* (cf. fig. 9).

The amplitude stabilizer

Section *2* of fig. 12 represents the amplitude stabilizer. The square-wave output of the flip-flop *1* alternately cuts off one of the two pentodes, type E 180 F. The current through the other one is determined entirely by a third pentode (an EF 80) in the common cathode lead of the two E 180 F valves. This third pentode functions as a source of constant current (partly by virtue of the cathode resistor R_k, which is not decoupled and which therefore introduces negative feedback); the magnitude of the current can be varied with potentiometer P_3. Since the current flowing through one of the two E 180 F pentodes is thus held constant, the voltage drop it causes in the anode resistance is also constant. This means that the output pulses have a constant amplitude.

Output stage of pulse shaper

If the pump circuits were to be connected directly to the amplitude stabilizer, they would constitute such a heavy capacitative load that the pulse edges would no longer be steep enough for the pulses in a rapid succession to retain a flat top and constant

[11]) Using a double triode E 88 CC (which has a higher transconductance than type E 92 CC) in conjunction with anode resistances of 1200 ohms and suitably adapted coupling networks, it has proved possible to reach count rates as high as 30×10^6 pulses per second for regularly-spaced pulses.

amplitude. For this reason the amplitude stabilizer must be followed by an output stage which on the one hand constitutes a very low capacitative load on the stabilizer and on the other has a low output impedance.

In both respects the White cathode-follower arrangement using two pentodes in series (see section *3* of fig. 12) is particularly efficient; EL 83 pentodes are used in order to obtain a square-wave output of 30 V amplitude. The effective input capacitance C_i is in this case:

$$C_i = (1-A)C,$$

where C is the "geometric" input capacitance and A the amplification. Since the latter is somewhat less than unity with a cathode follower, C_i is much smaller than C. The output impedance Z_0 is:

$$Z_0 = \frac{R_i\,(R_i + R_a)}{(S^2R_i^2 + SR_i + 1)R_a + (SR_i + 2)R_i},$$

where R_i is the internal resistance and S the slope (transconductance) of the valves, and R_a the anode load. If we substitute for R_i and S in this formula the values applicable to the EL 83, we find that R_a can be so chosen that Z_0 assumes a very low value, of the order of ten ohms. Such a value is quite small enough for feeding a series of pump circuits, even where pulses are involved with rise and decay times of about 4×10^{-8} sec.

Performance of the logarithmic counting channel

It will be evident that with the pulse shaper and pump circuits described above it is possible to build both linear and logarithmic count-rate meters capable of very high count rates. Calibrations have confirmed this. As regards the logarithmic instruments, fed for example by pulses from a scintillation counter, we have already seen in fig. 10 that the linear relation between the meter deflection and log n is still valid at $n = 3\times10^6$ pulses per second. The deviations from linearity in the whole range of $6\frac{1}{2}$ decades nowhere exceed 10% of the local value.

In conjunction with the millivolt discriminator discussed earlier, this logarithmic count-rate meter lends itself particularly well for measuring the neutron flux in a nuclear reactor. Photographs of the instruments as used in the KEMA reactor can be seen in *fig. 13a* and *b*.

The neutron detector itself must obviously be capable of delivering pulses at the high rates mentioned. The detector containing ^{10}B cannot do this, but the fission chamber can. The drawback that a gain of about 10^5 is required between this counter tube and a discriminator of the conventional type is not applicable in the apparatus described above; in this case the gain (in fig. 1, from A_1 and A_2 together) need only be 100.

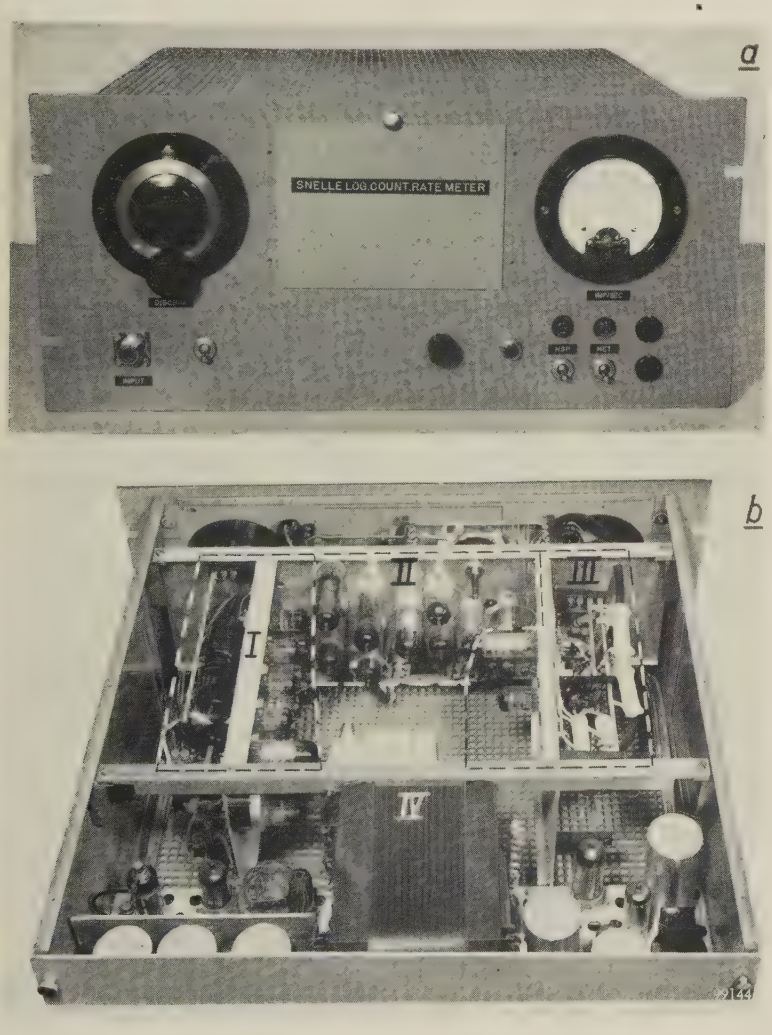

Fig. 13. Pulse-counting channel with logarithmic scale as developed and built in the KEMA laboratory. *a*) Front view; left, the potentiometer knob for setting the discrimination threshold; right, the meter with a logarithmic scale covering $6\frac{1}{2}$ decades. *b*) Interior view, showing the pump circuits *I*, the pulse shaper *II*, the discriminator *III* and the power pack *IV*.

Summary. The article describes the pulse-counting channels used in conjunction with a neutron detector for monitoring the neutron flux in the KEMA subcritical suspension reactor at Arnhem. Various components of the system were developed

and built in the KEMA laboratory, notably the "millivolt discriminator" which operates reliably with pulses from 12 mV at count rates of several million pulses per second, and an improved fast-response flip-flop in the pulse shaper, capable of handling up to 15 million pulses per second. The linear integrator consists of a "pump circuit", and the logarithmic integrator of eight pump circuits in parallel. In the latter a logarithmic relation exists between the meter deflection and the count rate n, extending from $n = 1$ to $n = 3\times10^6$ pulses per second ($6\frac{1}{2}$ decades). This property makes the logarithmic count-rate meter very suitable for monitoring the increase in neutron flux when a nuclear reactor is started up.

IIIB. THE MONITORING OF HIGH NEUTRON FLUX WITH THE AID OF AN ELECTROMETER

by M. van TOL.

621.039.564.2:621.039.524.46

In the case of the KEMA subcritical suspension reactor [1]), "high" neutron flux comprises flux values from about 2×10^3 to 2×10^6 neutrons per cm^2 per second, corresponding to a generated power of 1 mW to 1 W. To measure the flux in this range, the direct-current output of an ionization chamber filled with gaseous boron-trifluoride ($^{10}BF_3$) is measured [2]).

The design of the monitoring system was based on the following considerations:

1) At a neutron flux of 2000 neutrons per cm^2 per second, the ionization chamber delivers a current of 2×10^{-11} A.
2) This current — the smallest required to be measured — must produce a distinctly readable deflection; the latter is taken to be four scale divisions on a linear scale graduated up to 100.
3) For safety reasons the neutron-flux meter must remain in operation in the event of a mains failure.
4) For the same reasons the system must consist of two identical channels, each channel being fully independent of the other.
5) Each of the two channels must also serve to vary the position of a control rod via a servo-mechanism, thus keeping the neutron flux constant.
6) Both channels must be designed for connection to a recording instrument and a remotely positioned meter.
7) It must be possible to stop the reactor within 0.5 sec in any of the following contingencies:
   a) if the neutron flux exceeds a certain level,
   b) in the event of a mains failure,
   c) if the voltage on the ionization chambers falls off,
   d) if a defect occurs in the neutron-flux meters themselves.

Some of these points will be discussed at greater length below.

Electrometer with vibrating capacitor

For measuring the ionization current, which is of the order of 10^{-11} to 10^{-7} A, use is made of a vibrating-reed electrometer based on a principle which has been described in this journal [3]). The current passes through a high resistance R_1, and the direct voltage produced across it is converted into an alternating voltage by means of a vibrating capacitor. This is an air capacitor consisting of two parallel plates, one of which is stationary and the other kept in vibration. When the direct voltage is applied to the vibrating capacitor, an alternating voltage is produced between the plates which is proportional to the voltage across R_1 (cf. the operation of a condenser microphone). The alternating voltage is amplified and rectified, producing at the output a direct current that causes the deflection of a moving-coil meter. The deflection is a linear measure of the neutron flux. The vibrating capacitor is driven by a kind of loudspeaker movement powered by a valve oscillator; the frequency is 140 c/s. A block diagram is shown in *fig. 1*.

To prevent the sensitivity from being affected by mains voltage fluctuations and changes in valve characteristics, strong negative feedback is applied: a certain fraction β of the direct voltage output E_2 is added in opposite polarity to the input voltage E_1 across the high resistance R_1. The direct voltage converted into an alternating voltage is thus $E_1 - \beta E_2 = E_1'$. Taking the ratio $E_2/E_1' = A'$, the gain ultimately obtained, $E_2/E_1 = A$, is found to be:

$$A = \frac{E_2}{E_1} = \frac{A'}{1+\beta A'}.$$

[1]) J. J. Went, Instrumentation for a subcritical homogeneous suspension reactor, I. Reasons behind the choice of a homogeneous suspension reactor, Philips tech. Rev. **21**, 109-121, 1959/60 (No. 4/5).

[2]) See the reaction (1) in article IIIA of this series (p. 135).

[3]) J. van Hengel and W. J. Oosterkamp, A direct-reading dynamic electrometer, Philips tech. Rev. **10**, 338-346, 1948/49.

If $\beta A'$ (the loop gain) is large with respect to 1, we can write, to a good approximation:

$$A \approx \frac{1}{\beta},$$

so that the ultimate gain A is virtually independent of the gain A' of the valve circuit, which varies with the supply voltages and with the characteristics of the valves. In our case $\beta A' = 50$; with this value, a very constant value of A is obtained.

The values of β and A', separately, follow from the extreme values of E_1 and E_2. The lowest current required to be measured, 2×10^{-11} A, must produce a deflection of four scale divisions. The full deflection of 100 scale divisions therefore corresponds to a current of $25\times2\times10^{-11} = 5\times10^{-10}$ A. This produces across the resistor R_1, which is 200 MΩ, a voltage E_1 of 0.10 V. The output voltage E_2 required to cause full deflection of the meter is 2 V. The total amplification must therefore be $E_2/E_1 = 20$. For this purpose $^1/_{20}$ of the output voltage must be fed back to the input. Since we decided on $\beta A' = 50$, the nominal gain A' must be 1000.

Measuring ranges

As mentioned above, the high neutron-flux range covers three decades. Since the scale is linear, this range must be divided into separate ranges, in this case into six. The same constancy is required for all these ranges ($\beta A' = 50$) and in each case a value of $E_2 = 2$ V is required for full deflection.

The values referred to above, viz. $\beta = {}^1/_{20}$, $A' = 1000$ and $R_1 = 200$ MΩ, apply to the measuring range having the greatest sensitivity (position I): full deflection at 5×10^{-10} A. In positions II and III, β is greater by a factor of $\sqrt{10}$ and 10, respectively, and the sensitivity is therefore lower by the same factor; the currents that deflect the needle to the end of the scale are accordingly 1.6×10^{-9} A and 5×10^{-9} A, respectively. At the same time as β is increased, A' is reduced by the same factor, so that the product $\beta A'$ remains constant.

In positions IV, V and VI, β and A' have the same values as in positions I, II and III, but the value of resistance R_1 is reduced to $200/(10\sqrt{10})$ MΩ. In the range of lowest sensitivity (position VI) full deflection is therefore obtained with a current of $10\sqrt{10}\times5\times10^{-9} = 1.6\times10^{-7}$ A.

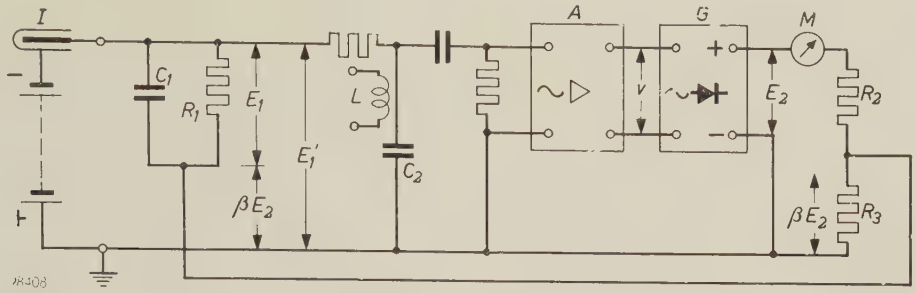

Fig. 1. Illustrating the principles of the monitoring system for high neutron flux. *I* ionization chamber. R_1 resistance of 200 MΩ (max.) with shunt capacitance C_1 for smoothing voltage variations caused by statistical fluctuations in the neutron flux. C_2 vibrating capacitor with driving coil *L*. *A* A.C. amplifier (with two EF 40 pentodes in cascade). *G* phase-sensitive rectifier (see fig. 4 and caption of the article quoted under [3]). *M* moving-coil meter. R_2-R_3 voltage divider from which the negative feedback voltage βE_2 is tapped.

Details of the voltage divider R_2-R_3 (fig. 1), from which the negative feedback voltage βE_2 is tapped, are shown in *fig. 2*. The figure also indicates the means of providing a signal required by the safety system (see article IV) as well as a connection for a recording instrument. The latter can be arranged to actuate a servomechanism, which varies the position of a control rod in such a way as to keep the neutron flux constant.

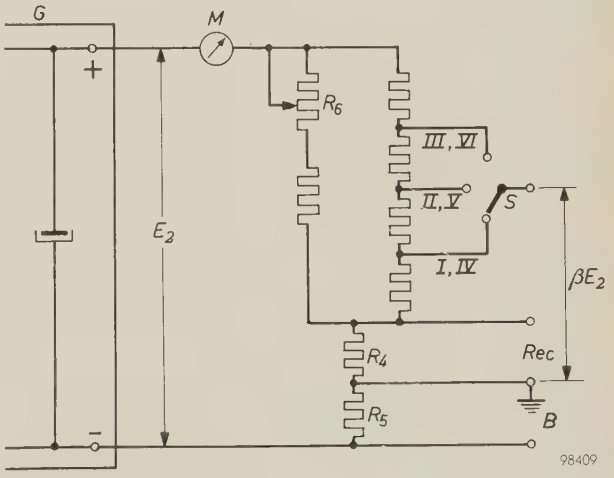

Fig. 2. Details of the voltage divider R_2-R_3 (fig. 1). *G* rectifier. *M* moving-coil meter. *S* measuring-range switch: $\beta = 1/20$ in positions I and IV, $\beta = \sqrt{10}/20$ in positions II and V, $\beta = 10/20$ in positions III and VI. Recording instrument *Rec* is connected in parallel with the low resistance R_4. The voltage across R_5 provides the signal actuating the safety system if certain limits are exceeded (see article IV); the safety system is connected at *B*. R_6 correction potentiometer.

Calibrating device

Neutron-flux meters are the chief instruments employed for controlling the operation of a nuclear reactor. If only for this reason it is desirable to be able to ascertain at any time whether these instruments are working properly. This is all the more important if, as in the KEMA reactor, the neutron-flux meters also supply the signal that puts the safety system into operation in the event of a dangerous situation arising.

The principle of the calibrating device is shown in simplified form in *fig. 3*. Fig. 3*a* shows the method of charging-up a capacitor C_3 of 50 μF which, during calibration (fig. 3*b* and *c*) acts as the source of anode current for an EF 40 pentode, whose control-grid and screen-grid potentials are constant. During the approximately 200 μA discharge, which takes place during the calibration (fig. 3*b* and *c*), the voltage on the capacitor obviously falls. For about 12 sec, however, this has no perceptible effect on

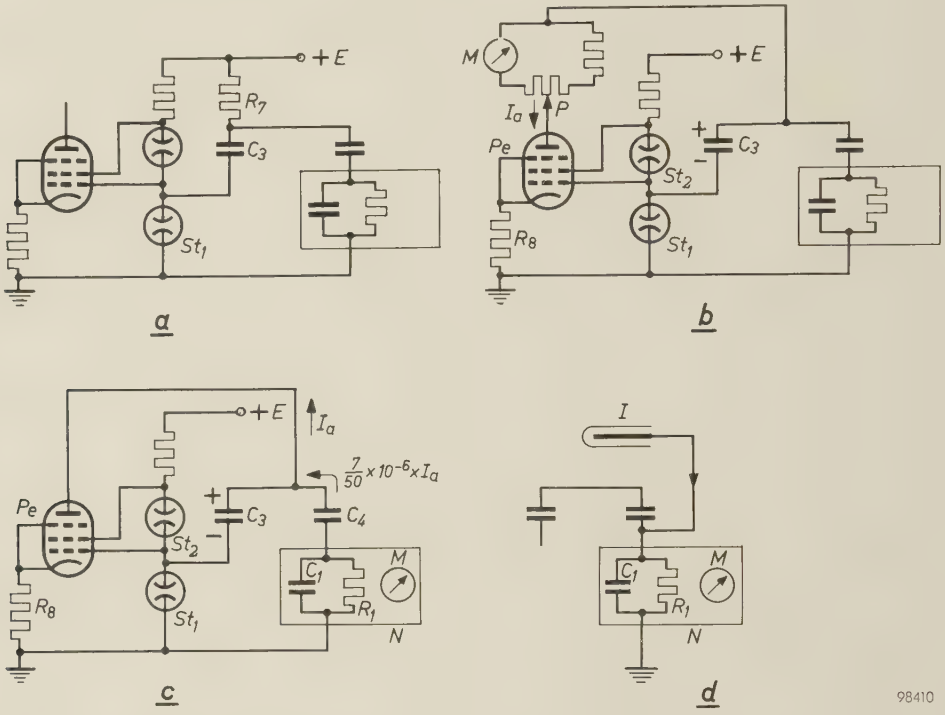

Fig. 3. Calibrating device for the neutron-flux monitoring system.
a) Via the resistor R_7 and the voltage-reference tube St_1 the capacitor C_3 (50 μF) is charged up from the direct-voltage source E.
b) The charged capacitor C_3 now discharges into the anode circuit of the pentode Pe (EF 40), whose control-grid and screen-grid potentials are kept constant by the voltage-reference tubes St_1 and St_2, and whose cathode resistance R_8 contributes to keeping the anode current I_a constant. This discharge current (approx. 200 μA) flows through the parallel circuit of the moving-coil meter M (now entirely disconnected from the neutron-flux monitor) and a shunt. The potentiometer P is preset such that M gives a certain standard deflection.
c) Checking the neutron-flux meter reading against the standard deflection obtained in (*b*). I_a now distributes itself over the capacitors C_3 (50 μF) and C_4 (7 pF) of a capacitative attenuator. The current through C_4 is $\frac{7}{50} \times 10^{-6} \times I_a$ and flows through the resistor R_1 (200 MΩ) in the flux monitor N; the moving-coil meter M must now give the same reading as in (*b*).
d) The flux monitor in normal operation, connected to the ionization chamber I. The calibrating device is out of operation.

The neutron-flux meter described is therefore equipped with a calibrating device, with which a known current can be applied for a short time to the 200 MΩ resistor R_1. This current is obtained by making use of the property of a pentode that, when the control-grid and screen-grid potentials are kept constant, the anode current remains, for a wide range of potentials, virtually independent of the anode voltage.

the anode current, owing to the pentode property referred to, and partly owing to the negative feedback, effected via the cathode resistance R_8. During the calibrating proper (fig. 3*c*), a capacitative attenuator C_3-C_4 ensures that a certain fraction ($\frac{7}{50} \times 10^{-6}$) of the said current flows for calibration purposes through R_1.

The calibration procedure is as follows. After capacitor C_3 has been charged up as in fig. 3*a*, the system is switched to

the circuit shown in fig. 3*b*. C_3 now discharges with a current I_a of about 200 μA, kept constant by the pentode. Part of this current flows through the moving-coil meter M (fig. 1), which for the moment is entirely disconnected from the neutron-flux meter. A preset shunt (potentiometer P) ensures that the meter gives a certain standard deflection. Next, after recharging as in (*a*), the system is switched over to the circuit in fig. 3*c*. The meter (with unchanged shunt) is now connected in the normal way in the output circuit of the neutron-flux meter, and the constant current I_a distributes itself over the capacitor C_3 (= 50 μF) and C_4 (= 7 pF). The portion now flowing via C_4 amounts to $^7/_{50} \times 10^{-6} \times I_a$, and this is conducted through the input resistor of the neutron-flux meter and produces a reading on meter M. The ratio $C_3 : C_4$ of the capacitative attenuator is chosen such that the deflection, provided there is nothing wrong with the neutron-flux meter, is the same as that in the case of fig. 3*b*. Finally, fig. 3*d* shows the normal flux-monitoring situation, with the calibrating system switched off.

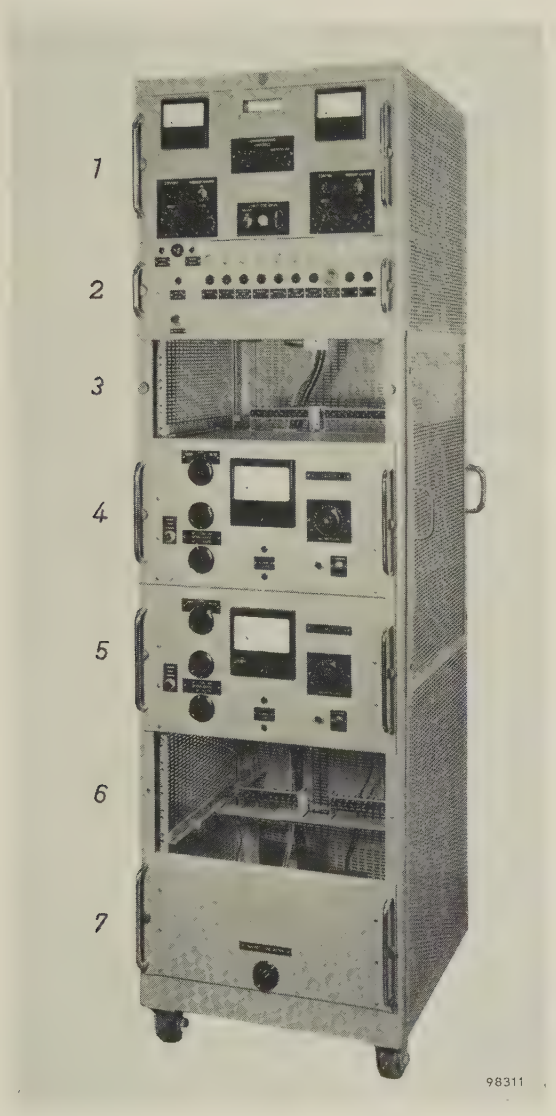

Fig. 4. The monitoring, control and safety equipment built by Philips for the KEMA subcritical suspension reactor. The units *1* to *7* contain the following:
Unit *1*: High-tension rectifiers and comparator circuit (with light-relay) for the potentials on the ionization chambers (see article IV of this series).
Unit *2*: Safety circuits, and pilot lamps that indicate which safety circuit has first operated (see article IV).
Unit *3*: Space for control panel of the temperature control system (see article II).
Units *4* and *5*: Identical neutron-flux monitoring channels based on electrometer system.
Unit *6*: Space reserved for future equipment.
Unit *7*: Unit of the temperature-protective system (see article IV).

Varying contact potentials may cause the meter M to deflect even though no current is applied to the neutron-flux meter. This error can be corrected with a potentiometer which supplies a small variable direct voltage in series with the vibrating capacitor.

Power supply

Each of the two identical flux-monotoring channels is powered by its own 6 V battery; they are thus entirely independent of the mains and independent of each other. Heater currents are taken directly from each battery, which also supply the current for D.C. motor generators that produce the H.T. voltages of 300 V.

The ionization chambers require a direct voltage of about 2500 V. This is obtained in a manner similar to that used for generating the E.H.T. for the picture tube in a television set [4]); the high-frequency output of an oscillator is stepped up by a transformer, rectified and smoothed to a direct voltage of 2500 V. Part of this voltage is compared with a reference voltage and the deviation from the latter is used for controlling the oscillator. In this way the E.H.T. is stabilized. The oscillator is fed from the battery and the motor generator.

Fig. 4 shows the actual equipment. Apart from the neutron-flux monitoring channels discussed above, it also contains the safety circuits, which are dealt with in the following article.

[4]) See e.g. Philips tech. Rev. **10**, 125, 1948/49, or **14**, 21, 1952/53.

Summary. Description of the monitoring system used in the KEMA subcritical suspension reactor for measuring the neutron flux in the range 2×10^3 to 2×10^6 neutrons per cm^2 per second. For this purpose an ionization chamber and vibrating-capacitor electrometer are used. The electrometer has strong negative feedback (loop gain 50); the meter has six measuring ranges and a linear scale. The minimum and maximum currents that produce full deflection are 5×10^{-10} and 1.6×10^{-7} A, respectively. A calibrating device is incorporated for checking the operation of the instruments at any time. The monitoring system consists of two identical channels; each channel is powered from its own battery.

IV. THE SAFETY CIRCUITS

by F. J. SCHIJFF.

621.039.524.46:621.039.587

Protective system with safety rods

Nuclear reactors must be safeguarded by a protective system against the possibly disastrous consequences of faults in operation or defects in the apparatus. If, for example, the neutron flux in the reactor should become excessive or increase too rapidly, if the temperature should become too high, or a neutron-flux meter fail to give a reading, or any other abnormality occur, the reactor must be automatically stopped. As a rule this is done by causing rods of neutron-absorbent material (safety rods) to drop quickly into the reactor, thereby discontinuing or preventing the occurrence of the chain reaction. A conventional arrangement is to suspend the safety rods from electromagnets (*fig. 1a*); when the current energizing the magnets is interrupted, the safety rods drop into the reactor. The magnet currents are interrupted by means of relays, which respond to the abnormalities against which the reactor is to be safeguarded. A protective system of this type has already been described in this journal [1]).

The KEMA subcritical suspension reactor [2]) is also safeguarded in this manner. In this case three safety rods of boron carbide are used, one of which serves as control rod. These rods do not fall into the reactor vessel but into the neutron reflector surrounding it; see fig. 5 of article I of this series.

Both for accurately measuring the various quantities (neutron flux, temperature, etc.) and for protective purposes, detectors are required that convert the quantity concerned into an electrical signal. In principle, the same detectors can serve both purposes. It is preferable, however, for a safety system to have its own detectors, since those used for accurate measurements are an integral part of a complicated apparatus and are required to be extremely sensitive. These conditions are not always compatible with the primary requirement of a protective system which is to ensure *maximum safety* (certain and prompt intervention when necessary) and reasonable *reliability* (failures that give rise to spurious interventions should be rare). The very

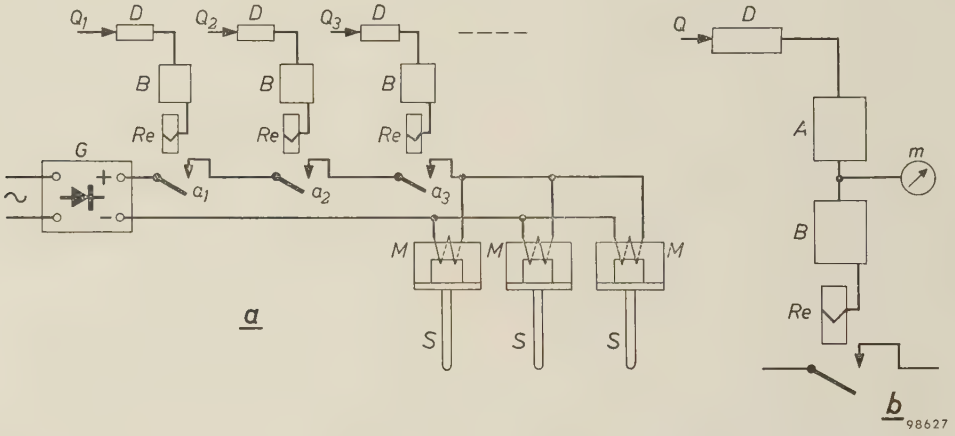

Fig. 1. *a*) Principle of a safety circuit for a nuclear reactor. The detectors D for the quantities Q_1, Q_2, Q_3, ... (neutron flux, temperature, etc.) supply a signal to the circuits B, each of which energizes a relay Re. Via the relay contacts a_1, a_2, a_3, ... the rectifier G energizes the electromagnets M from which the safety rods S are suspended. If one of the quantities Q reaches a critical value, the associated relay cuts out, the current through the electromagnets is interrupted and the rods S drop, thereby preventing any further increase in the neutron flux.
b) In the KEMA reactor there is no space for separate detectors in the safety systems. The circuits B obtain their signal from the measuring channels A (with detector D and meter m); A may be e.g. a neutron-flux meter, a period meter, a temperature meter, a flow meter, etc.

[1]) F. E. L. ten Haaf, G. Klein and F. J. Schijff, Monitoring, control and safety equipment for a nuclear reactor of the swimming-pool type, II. Further description of certain components units, Philips tech. Rev. **19**, 273-285, 1957/58, in particular pages 281-285.

[2]) J. J. Went, Instrumentation for a subcritical homogeneous suspension reactor, I. Reasons behind the choice of a homogeneous suspension reactor, Philips tech. Rev. **21**, 109-121, 1959/60 (No. 4/5).

compact design of the KEMA reactor, however, does not permit the use of separate detectors in the safety system; the same detectors, and to some extent the same amplifiers, therefore had to serve both for measurements and protection (fig. 1*b*). The difficulty was increased by the fact that measurements were to be made on this reactor at very low levels of neutron flux, which called for an extremely sensitive, and therefore delicate, measuring system.

The presence of complicated instruments in the protective system essentially entails a lower degree of both safety and reliability. Now the experimental nature of the KEMA reactor makes it possible to tolerate more frequent unnecessary scrams — i.e. a lower degree of safety-equipment reliability — than would normally be permissible. The following measures could therefore be taken to improve the safety factor, although with some sacrifice of reliability.

1) The principal measuring channels — likewise safety channels — were duplicated.
2) Upper-limit as well as lower-limit protection is provided: the safety circuit coupled to the measuring channel intervenes not only when the parameter concerned exceeds a certain value, but also when the output signal of the measuring channel is too small (which might indicate a defect).

In this way a safeguard is obtained against the great majority of faults that can occur in the measuring channels; a fault whereby the meter reading lay between the two limits is very unlikely. The system thus possesses in large measure fail-safe characteristics: almost any conceivable defect in the protective system causes the safety rods to drop.

Thyratron circuit

In the circuits denoted *B* in fig. 1*b*, use is made of a tetrode thyratron, type PL 5727, which has two grids. The circuit arrangement is shown in *fig. 2a*. The thyratron anode load is fed by an alternating voltage of 50 c/s frequency. The range of input voltages V_i within which the thyratron ignites, extends from —0.20 V to —1.6 V, corresponding respectively to the lower and upper limits of the detected quantity Q. When V_i is between these limits, the thyratron passes a current pulse during each cycle. This current energizes the relay, keeping its contact closed and thereby energizing the D.C. electromagnets from which the safety rods are suspended. If Q reaches the upper limit ($V_i = -1.6$ V), the potential on the second grid of the thyratron is such as to just prevent the thyratron from igniting. The relay then cuts out, the magnet current is interrupted and the safety rods drop. If Q drops to the lower limit ($V_i = -0.20$ V), a transistor circuit ensures that a negative voltage is applied to the first grid sufficient to cut off the thyratron, with the same result. Further details of the operation of this circuit are given in the caption to fig. 2.

The input voltage V_i must be negative with respect to earth. For this reason the neutron-flux monitoring channel, described in article IIIB, contains an earthed tapping on the output voltage-divider (see fig. 2 of article IIIB); the voltage between the negative terminal and the tap serves as V_i.

Relays with *make*-contacts are used which are in the energized state during normal running; if a relay should cut out, for whatever reason, the electromagnet current is broken. This is important, for it provides the fail-safe feature: most faults likely to occur in the safety system, including supply failures, lead to the current through the relay coil being cut off, and hence to the shutdown of the reactor. Another important point in this connection is that the relays are D.C. relays, energized from an A.C. source via a rectifying element (the thyratron). Short-circuiting between anode and cathode or between anode and grid will thus open the relay.

Several of the above-mentioned features are also to be found in the safety system for the research reactor at the Technische Hogeschool, Delft (see the article cited under [1])). This system is in fact a further development of the circuit for the KEMA reactor, and was designed in 1955. The system used in the Delft reactor is fail-safe to an even higher degree; it is also considerably more reliable, owing to the use of a reduced number of components and, in particular, of independent detectors. The time required to stop the reactor is shortened by choosing the frequency of the alternating voltage in the anode circuit of the thyratron as 2000 c/s; with the subcritical KEMA reactor the time delay between detector signal and rod motion may permissibly be as long as 0.5 sec, for which a frequency of 50 c/s is sufficient.

The following are some of the features contributing to increased safety and reliability. The PL 5727 thyratron is a "Special Quality" valve [3]), and thus very reliable in itself. Two base pins are provided for the second grid, and both are used (fig. 2*a*), thus minimizing the risk of a broken grid connection (in which case the valve would pass current when it ought to be cut off). The relay coil is wound with thin wire, and therefore the risk of wire breakage due to corrosion cannot be excluded; this is countered by providing the coil with a second winding (the "anti-corrosion winding" w', fig. 2*a*),

[3]) Philips tech. Rev. **18**, 181, 1956/57.

which is connected at one end only and gives a degree of cathodic protection against corrosion of the main winding in the case of leakage currents.

Situations in which the safety system enters into operation

We shall now briefly review the situations in which the safety system enters into operation.

2) *Reactor period too short.* A short period means that the neutron level is rising too rapidly, and is therefore dangerous. As mentioned in article IIIA, the period is measured by differentiating the signal from the logarithmic neutron-flux meter. In the interest of reliability this is also done via two mutually independent channels. Each channel can operate the safety circuit.

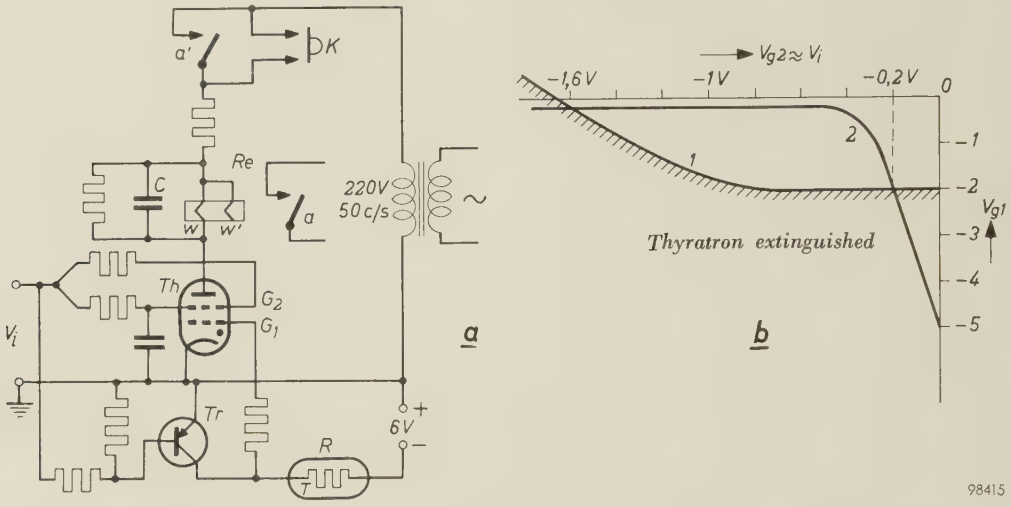

Fig. 2. *a*) Diagram of one of the identical safety circuits (*B* in fig. 1) together with relay *Re* (showing main winding *w*, anti-corrosion winding *w'*, contacts *a* and *a'*, and smoothing capacitor *C*). *Th* thyratron type PL 5727. *K* push-button re-set contact, in parallel with take-over contact *a'* of *Re*. *Tr* transistor type OC 71. The range of input voltages V_i in which the thyratron can ignite extends from —0.20V to —1.6 V, corresponding respectively to the lower and upper limits of the detected quantity *Q*.
b) Curve *1* gives the combinations of grid-voltage values V_{g1}-V_{g2} at which the thyratron, operated on a sinusoidal anode voltage of 220 V r.m.s., is just able to ignite. When the thyratron is extinguished, V_{g2} is virtually equal to V_i. Curve *2* shows the relation between V_{g1} and V_{g2} ($\approx V_i$) given by the transistor circuit.
Depending on the magnitude of V_i, three cases can be distinguished:
1) $V_i < -1.6$ V. In this case the transistor base voltage is sufficiently negative to allow the transistor to pass a high collector current I_c. The potential difference between emitter and collector is then very small, and therefore the potential on grid g_1 is practically equal to that on the cathode. Curve *1* shows that in this state ($V_{g1} \approx 0$, $V_{g2} < -1.6$ V) the thyratron passes no current.
2) $0 > V_i > -0.20$ V. The base voltage of *Tr* is now much less negative than in case 1). Consequently I_c is much lower and so therefore is the potential drop across the resistor *R*. Suppose that I_c is now zero: then the potential drop across *R* is also zero, and therefore $V_{g1} = -6$ V, whilst again $V_{g2} \approx V_i$. According to curve *1*, the thyratron again passes no current. However, I_c is not entirely zero but has a certain residual value, which increases steeply with the temperature of the transistor. V_{g1} is thus not so negative as —6 V, but if the temperature is not too high it is sufficiently negative to prevent the thyratron from igniting. To reduce the temperature effect, a resistor having a negative temperature coefficient is used for *R* (thermistor).
3) -0.20 V $> V_i > -1.6$ V. This is the case during normal safe running. V_{g1} and V_{g2} are now such that the thyratron can ignite when the anode circuit is closed by pushing the re-set button *K*. The relay is then actuated and closes the contacts *a* and *a'*, after which *K* can be released without the anode circuit being broken.

1) *Excessive neutron flux.* The neutron flux is measured via two entirely independent channels (see article IIIB), each with its own indicating instrument. As soon as the neutron flux reaches a level corresponding to 125% of the full-scale deflection, the upper-limit protection comes into operation. If the reading drops below 15% of the full-scale deflection, the lower-limit protection takes over.

3) *The voltage applied across the neutron detectors differs from the nominal value.* If, owing to some defect or other, the fixed potential on the neutron detectors should drop appreciably or fall off altogether, the signal from the neutron-flux channels will be too small to produce an adequate reading and therefore the lower-limit protection will come into operation.

Measures are also needed, however, to deal with the contingency of a relatively slight deviation of the voltage from its nominal value, since the voltage affects the sensitivity of the special neutron-flux detectors used (ionization chambers with some "gas amplification"). To avoid the use of highly sensitive and thus less robust voltmeters, the following method was adopted. The two neutron detectors are each fed from separate direct-voltage sources, the outputs from which are constantly compared. If the voltage difference exceeds 5 V, the safety system intervenes in the manner described below. The basic assumption is that the chance of the two voltages dropping simultaneously with a mutual difference of less than 5 V is negligible (unless both voltages fail, in which case, however, the lower-limit protection enters into operation, as described).

The difference between the two voltages (reduced by a small, variable zeroing voltage) is indicated by a voltmeter V (*fig. 3*), whose zero point is in the centre of the dial. This meter also functions as a relay [4]): when the needle reaches the one or other end of the scale, it intercepts a beam of light from an electric bulb, which is normally incident on a phototransistor. As soon as the latter receives no more light, the current it passes drops almost to zero, thereby actuating the safety system.

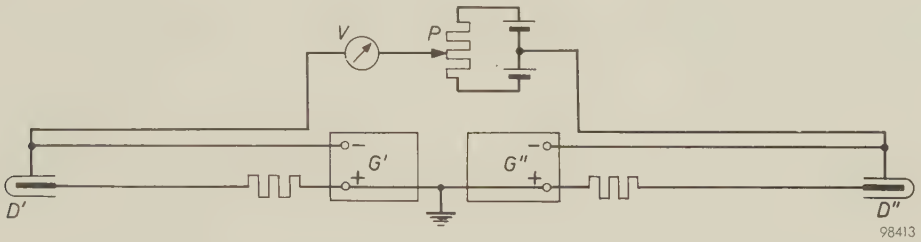

Fig. 3. Protective circuit that detects any deviation from the nominal voltage across the neutron detectors. It is assumed that the chance of both voltages dropping simultaneously at the same rate (i.e. differing by less than a few volts) is negligibly small. The one voltage thus serves as reference voltage for the other.
D', D'' neutron detectors, with voltage supplies G', G''. The difference between the voltages on D' and D'' (initially zeroed by a voltage derived from potentiometer P) is indicated by the voltmeter V, which also operates as a relay.

4) *The measured temperature differs from the preset value.* In article I it was explained that the reactivity of a suspension reactor has a negative temperature coefficient, which operates so promptly as to prevent a thermal run-away when the reactor is delivering power. The reactor under discussion, however, is used only for subcritical experiments (and hence has no significant power output). For the purposes of measurement it is provided with a temperature control system which automatically keeps the temperature in the reactor vessel constant within narrow limits (see article II of this series). It is conceivable that, owing to a defect in this control system or to improper handling, a drop in temperature might occur. Because of the negative temperature coefficient, this would be accompanied by an increase in the neutron flux. Although the above-mentioned measures exist to deal with excessive neutron level and a too rapid increase in neutron flux, for additional safety a further provision is made which brings the safety system into operation when the temperature differs more than 2 °C from the preset value.

5) *The suspension circulates too slowly.* If the flow rate of the suspension is too slow, the result may be an insufficiently homogeneous distribution of the fuel particles in the water. This gives rise to concentrations of fissile material that might prove dangerous. A flow-rate meter delivers a signal which, in the event of inadequate flow, actuates the safety system.

6) *Mains failure.* A mains failure deprives the thyratron anodes of their alternating-voltage supply. All safety relays then cut out and the magnet circuits are broken; the mains failure of course means in any case that the magnet current falls to zero.

Rod-position indication

Since the safety rods themselves are not visible, there should be some means of indicating whether they are still suspended from the electromagnets or have dropped into the reactor. In the KEMA reactor this indication is obtained in the following way. Use is made of the fact that the inductance of the magnet coils is higher when the magnetic circuit is closed by the safety rod than when it is open as a result of the rod being dropped. Each coil is bypassed by a capacitor (*fig. 4*) whose value is such that the circuit resonates at the ripple frequency (50 c/s) of their rectified supply voltage when the

[4]) See article mentioned under [1]), page 280.

rods are *not* suspended from the electromagnets; the ripple voltage across the coil is then considerable. A voltmeter connected to the circuit via small coupling capacitors gives full-scale deflection in

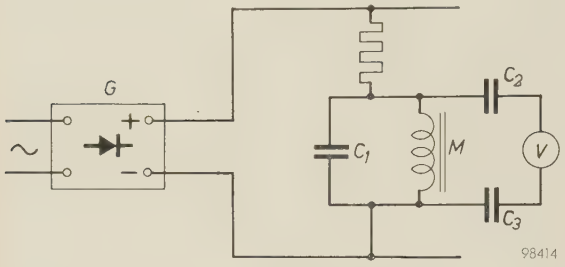

Fig. 4. Circuit for indicating the position of the safety rods. M electromagnet. C_1 parallel capacitor which causes the circuit M-C_1 to resonate at the ripple frequency of the output from rectifier G when the safety rod is *not* attached to the magnet M. V A.C. voltmeter. C_2, C_3 coupling capacitors.

this case. When the rods are connected to the magnets, the ripple voltage is so much lower than at resonance that the meter gives only about 50% of full-scale deflection. We thus have the following cases:

Meter reading 50% . The safety rods are still attached to the magnets. The situation is normal.

Meter reading 0 . . . No ripple voltage across the coil. The safety system has worked and the rods have dropped.

Meter reading 100% . The electromagnets are again energized, but the rods are not yet attached to them.

This meter, then, shows at a glance the position of the safety rods. If they have dropped, a pilot lamp (see fig. 4 of article IIIB) lights up to show which safety channel entered into operation first.

Summary. The KEMA subcritical suspension reactor contains three safety rods of boron carbide, which are suspended from electromagnets, the energizing current for which flows through a number of relay contacts in series. If one of the relays cuts out, the rods drop and the reactor is stopped. Each of the relays receives its energizing current via a thyratron, which can ignite only when its input voltage V_i is between −0.20 and −1.6 V, corresponding respectively to the lower and upper limits of the quantities to which the safety system is required to respond (neutron flux, reactor period, temperature, suspension flow-rate, etc.). The voltage V_i is taken from the channels used for monitoring these quantities. Measures are taken to make the system "fail-safe".

LABELLING OF COMPOUNDS WITH RADIOACTIVE TRACERS

The preparation of chemicals labelled with β-active isotopes must be done in such a way that the operator is not exposed to an atmosphere contaminated by dustborne or volatile radioactive substances). The work is therefore done in a "glove box", an air-tight box with a transparent window in which a number of long rubber gloves are sealed. The operator can thus manipulate the apparatus from outside. A small underpressure (5 cm water) is maintained in the box.

The photograph shows the operation of labelling tricresyl phosphate with the radio isotope ^{32}P, in the Isotope Laboratory of N.V. Philips-Duphar, Amsterdam. The preparation is used as a tracer in the oil industry.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk * can be obtained free of charge upon application to Philips Electrical Ltd., Century House, Shaftesbury Avenue, London W.C. 2.

2640: A. Kats: Spectres d'absorption du verre de silice et du quartz cristallin contenant des impuretés de Ge (Verres et Réfractaires **12**, 191-205, 1958, No. 4). (Absorption spectra of vitreous silica and crystalline quartz containing germanium; in French.)

The paper opens with an account of the investigations of Garino Canina relating to the absorption band at 2420 Å in vitreous silica, which have shown that this band is due to the presence of germanium. The author gives a detailed explanation of this phenomenon. The author's experiments on the irradiation of vitreous silica with X-rays have made it possible, with the aid of absorption spectra, to obtain precise data on the perturbations of the network and identification of the colour centres. The paper concludes with a table summarizing the results obtained on absorption bands and the types of colour centres formed by Ge and found not only in irradiated and non-irradiated vitreous silica but also in irradiated and non-irradiated crystalline quartz.

2641: J. A. Kok and M. M. G. Corbey: Aspects of electrical breakdown of liquid insulating material, I (Appl. sci. Res. **B 7**, 257-264, 1958, No. 4).

The electrical breakdown strength of insulating oil depends on the size of foreign particles which may form bridges in a place of maximum electric stress. The theoretical relation was verified with colloid suspensions of particles of known radius. Mineral oils may deteriorate if the particles unite by the process of flocculation, the occurrence of which depends on the relative magnitudes of the attractive London-Van der Waals forces acting between the particles and the repulsive forces between their ion atmospheres. The possibility of using a mineral oil as an insulator depends on the existence of an upper limit of the size of particle complexes due to the rapid fall-off of the L.-v. d. W. forces at diameters exceeding 500 Å. The latter diameter corresponds to a breakdown strength of 1 kV/mm. If acids are being formed, the upper limit of 500 Å will shift towards larger values, and correspondingly the breakdown strength may drop below 1 kV/mm.

2642: A. van Weel: Design of detector stages for signals with symmetrical or asymmetrical sidebands (J. Brit. Instn. Rad. Engrs. **18**, 525-538, 1958, No. 9).

The design of detector stages for signals with symmetrical-sideband components can be improved over conventional designs by properly using the long-established but not generally-known theory of such stages. For asymmetrical-sideband signals (e.g. television signals), an improved design is possible using the results of recent investigations. The condition for the i.f. amplitude curve to fall by a factor of two at the carrier frequency and for the v.f. section of the detector stage to have a wide-band transfer impedance are shown to be unjustified; it is shown that the correct design procedure is to consider the i.f. and v.f. sections of the detector stage together.

2643: J. Rodrigues de Miranda and J. J. Zaalberg van Zelst: New developments in output-transformerless amplifiers (J. Audio Engng. Soc. **6**, 244-250, 1958, No. 4).

An 11-watt audio power amplifier is described incorporating combined positive and negative feedback. The use of a Sinclair-Peterson type single-ended push-pull output stage enables an 800 ohm loudspeaker to be driven directly, providing excellent results. See also Philips tech. Rev. **19**, 41, 1957/58.

2644: P. Massini: Uptake and translocation of 3-amino- and 3-hydroxy-1,2,4-triazole in plants (Acta bot. neerl. **7**, 524-530, 1958, No. 3).

The uptake and translocation of radioactive 3-amino- and 3-hydroxy-1,2,4-triazole in various plants has been investigated. The first compound is taken up and translocated much faster than the second one upon administration to a leaf. The rate of uptake through the roots or through the cut-off stem is the same for the two compounds. The distribution of aminotriazole in the plants points to a translocation by the phloem system.

2645: W. J. Oosterkamp and J. Proper: The water equivalence of the phantom material Mix D for soft X rays (Brit. J. Radiol. **31**, 644, 1958; No. 371).

The phantom material "Mix D" (Jones and Raine,

Brit. J. Radiol. **22**, 549, 1949), Perspex, Philite and water have been compared as to their attenuation of X-rays generated between 23 and 50 kV constant potential. It is concluded that Philite (phenol-formaldehyde) approximates better than either Mix D or Perspex to water. (It has later been shown that the conclusion with regard to Mix D was not justified, the Mix D used not having had the prescribed composition; see W. J. Oosterkamp and J. Proper, Brit. J. Radiol. **32**, 560, 1959.)

2646: J. Brug and G. B. Paerels: Configuration of N-acetyl-neuraminic acid (Nature **182**, 1159-1160, 25 Oct. 1958).

The authors show that the condensation of oxaloacetic acid with N-acetyl-d-glucosamine as well as with N-acetyl-d-mannosamine in aqueous solution at *p*H 11 and at room temperature give rise to N-acetyl-neuraminic acid. It is shown that the N-acetylamino sugars epimerize under the conditions of the reaction.

From these results the authors corroborate the assumption of Comb and Roseman that the configuration of carbon atoms 5-8 in N-acetylneuraminic acid corresponds with the configuration of carbon atoms 2-5 in N-acetyl-d-mannosamine.

2647: A. Bril, H. A. Klasens and Th. J. Westerhof: On cathodo-thermoluminescence (Physica **24**, 821-827, 1958, No. 10).

The light output of some phosphors has been measured as a function of temperature from —180 up to 20 degrees centigrade. When the phosphors are measured in a demountable tube, strong maxima and minima can be found in the light output during heating of the phosphor from —180 °C to room temperature. This has also recently been described by Gobrecht, Hahn and Scheffler, who called this effect cathodo-thermoluminescence. A series of sealed and thoroughly outgassed tubes has been made. In these tubes, however, no indication of strong maxima and minima was found. The experiments lead to the conclusion that the cathodo-thermoluminescence does not seem to be a bulk property of the phosphors, but that it is more likely to be connected with gas adsorption on the phosphors.

2648: H. G. van Bueren: Plastic creep of germanium single crystals (Physica **24**, 831-837, 1958, No. 10).

The temperature and stress dependence of the creep rate of germanium single crystals, loaded in tension, have been measured. Three parts are distinguished in the creep curve. A theory is presented in which the initial part is explained in terms of the liberation of dislocation sources from impurity atoms, whereas the stationary creep rate attained in the second part is determined by the mobility of the dislocations themselves. This mobility is restricted owing to the occurrence of broken valence bonds along the dislocations. The third, work-hardening part of the creep curve is reached when the dislocation density in the material has reached a sufficient magnitude for piled-up groups to form.

2649: W. J. Oosterkamp: Meting en beperking van röntgenbestraling, ontvangen door onderzoekers bij doorlichting en het maken van foto's (Mens en Onderneming **12**, 387-390, 1958, No. 6). (Measurement and limitation of X-ray dose received by investigators during radiology; in Dutch.)

Review of the sources of radiation hazard for persons concerned with medical radiology and of the measures that may be taken to measure and limit the hazard.

2650: H. A. Klasens: The intensity dependence of photoconduction and luminescence of photoconductors in the stationary state (Phys. Chem. Solids **7**, 175-200, 1958, No. 2/3).

The properties of photoconductors and photoconducting phosphors are determined by states in the forbidden zone. Two models are considered for discussing the intensity dependence of their photoconduction and luminescence. In each model two recombination processes between electrons and holes are competing. It is shown that the one-state model, where direct recombination may take place between free electrons and free holes or via one impurity state, is generally not adequate. The two-state model with two discrete states having different capture cross-sections for capturing electrons and holes, can explain satisfactorily many aspects of these photoconductors quantitatively, such as superlinearity of luminescence and photoconduction, changes in power from 1 tot 0.5 in the conductivity versus intensity curves, activation and killing of phosphors, saturation, etc.

Duboc's method of considering all possible combinations between simplified versions of the equations describing the stationary state was applied successfully to give a mathematical description of the two-state model. Although there are 128 such combinations,all of which may occur under appropriate conditions,only a few occur in each individual case when onlythe intensity of excitation is varied. Others may appear when the temperature is varied. A few practical cases are analysed and the correct combinations of approximations determined. In particu-

lar, two examples of superlinearity are studied in detail. It appears that the general features of the curves can in both cases be described adequately in terms of the model with two discrete states, without having to introduce energy distributions of "ground states", as proposed by Rose. However, a problem remains in that the range of light intensity over which superlinearity occurs is much greater than is predicted by the simple model; it is possible that this can be explained e.g. by an inhomogeneous distribution of photoconductive excitation through the sample, due to strong absorption of the incident radiation.

2651: H. C. Hamaker: De recente ontwikkeling in proefopzetten met kwantitatieve factoren (Statistica neerl. **12**, 201-212, 1958, No. 4). (Recent developments in the design of experiments with quantitative factors; in Dutch.)

This paper reviews some recent developments in experimental designs for dealing with quantitative factors. The following topics are discussed: rotatable designs (Box), evolutionary operation (Box), experiments with mixtures (Scheffé), experiments with 10 to 100 factors (Satterthwaite), random vector experiments, the use of electronic computers in fitting non-linear models, and research strategy (McArthur).

2652: G. Meijer: Infrared fluorescence of copper-activated zinc sulphide phosphors (Phys. Chem. Solids **7**, 153-158, 1958, No. 2/3).

An infrared fluorescence was observed for ZnS:Cu,Al and ZnS:Cu,Ga at 1.57 μ and 1.72 μ. This emission appeared to be excited at low temperatures by radiation of 1.38 μ and of 0.5-0.8 μ, provided that the phosphor was excited by 3650 Å. The infrared quenching of the visible fluorescence and an infrared stimulation of the visible phosphorescence show a spectrum analogous to the infrared excitation spectrum, and seem to be connected with the same transitions.

2653: H. C. Hamaker: Some basic principles of sampling inspection by attributes (Appl. Statistics **7**, 149-159, 1958, No. 3).

Discussion of various approaches to one of the main problems in sampling inspection — that of deciding what size of sample to use. In particular, this paper discusses the extent to which our choice of sampling-inspection plans depends *a*) on knowledge of the distribution of the percentages defective in the inspection lots and *b*) on economic considerations. The opinion is expressed that these factors have a decided but crude influence, and that attempts to arrive at a precise economic theory of sampling-inspection procedures are doomed to fail in practice.

2654: M. J. Sparnaay: Corrections of the theory of the flat diffuse double layer (Rec. Trav. chim. Pays-Bas **77**, 872-888, 1958, No. 9/10).

The potential distribution in the diffuse part of the ionic double layer, which is formed at the interface between a solid and an electrolyte solution, is given by the Poisson-Boltzmann equation. This equation, involving some approximations, is modified such that now the following effects are included: 1) The effect of ionic sizes. 2) The effect of the dependence of the dielectric constant upon the ionic concentration and upon the electric field present near the interface. Two opposed tendencies can be distinguished here: *a*) the solution near the interface is polarized (Prigogine, Mazur and Defay), usually giving rise to a *de*crease of the ionic concentration near the interface; *b*) Coulomb interactions near the interface, between the ions and the interface, are different from those predicted from the unmodified theory. This will give rise to a relative *in*crease of the ionic concentration. It appears that tendency *b*) outweighs tendency *a*). A flat interface and a 1-1 electrolyte solution are considered only. The effects are represented as correction terms added to the original Poisson-Boltzmann equation. The new equation is integrated using elementary methods. The result of the calculations is that corrections are negligibly small when the electrolyte concentration is of the order of 10^{-3} normal. When the concentration is 10^{-2} normal, the corrections amount to 10-20% of the value of the double-layer potential, whereas the treatment breaks down, when the concentrations are 10^{-1} normal or higher.